Crew Factors in Flight Operations: The Initial NASA-Ames Field Studies on Fatigue

Fatigue Countermeasures Program
NASA-Ames Research Center
Moffett Field, CA

VOLUME 69
NUMBER 9, SECTION II, Supplement
SEPTEMBER 1998

AVIATION, SPACE, AND ENVIRONMENTAL MEDICINE

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Crew Factors in Flight Operations: The Initial NASA Ames Field Studies on Fatigue-- Preface

MARK R. ROSEKIND, PH.D.

SINCE 1980, NASA-Ames Research Center has examined the role of fatigue as a safety issue in flight operations. Over the years, activities have expanded to include field studies, controlled laboratory experiments, education and training programs, support for accident investigations, collaborative symposiums, policy support, and many other fatigue-related projects. Originally the Fatigue/Jet Lag Program, the project evolved into the NASA-Ames Fatigue Countermeasures Program. This highlighted the translation of research findings into effective and practical strategies that improve alertness and performance in flight operations.

During the 1980s, a series of unique field studies were conducted to document fatigue in different flight environments. This supplement reports four major field studies carried out during this period. Flight crewmembers were monitored before, during, and after regularly scheduled commercial trips in daytime short-haul (fixed-wing and helicopter) operations, overnight cargo operations, and long-haul operations. The methods involved subjective report and physiological measures that specifically focused on flight crew sleep and circadian factors. These studies provided a systematic scientific foundation for understanding the role of fatigue in flight operations and the development of operational countermeasures.

The first paper describes the objectives and methods common to all of the studies. The following four papers detail the findings from the four different operating environments. The final paper provides a summary overview that examines the different causes of fatigue in each operating environment and makes specific suggestions regarding approaches to reduce fatigue-related risks and to improve the safety margin.

This supplement provides an opportunity to report these methods, findings, and summary overview as an integrated scientific activity. Represented in this integrated fashion, these studies are an important contribution to the scientific understanding of fatigue in flight operations. These studies represent a significant amount of effort and resources. The many contributors are acknowledged in individual papers and appreciation is extended again to all of the critical participants that brought these activities to fruition.

This supplement is dedicated to two individuals: Charles E. Billings, M.D. and John K. Lauber, Ph.D. Drs. Billings and Lauber provided the critical elements, vision, and energy to initiate the NASA-Ames Fatigue/Jet Lag Program and undertake these critical first studies. Their contributions and support have continued over many years and represent the highest standards of scientific integrity, intellectual curiosity, and emphasis on operational relevance.

Flight Crew Fatigue I: Objectives and Methods

PHILIPPA H. GANDER, PH.D., R. CURTIS GRAEBER, PH.D., LINDA J. CONNELL, M.S., KEVIN B. GREGORY, B.S., DONNA L. MILLER, B.A., AND MARK R. ROSEKIND, PH.D.

GANDER PH, GRAEBER RC, CONNELL LJ, GREGORY KB, MILLER DL, ROSEKIND MR. *Flight crew fatigue I: objectives and methods.* **Aviat Space Environ Med 1998; 69(9,Suppl.):B1–7.**
In 1980, NASA-Ames Research Center, Moffett Field, CA, initiated a program to assess flight crew fatigue, determine its potential operational consequences, and provide practical countermeasure suggestions. To assess the extent of the problem, crewmembers were monitored before, during, and after commercial short-haul (fixed-wing and helicopter aircraft), overnight cargo, and long-haul operations. A total of 197 volunteers were studied on 94 trip patterns with 1299 flight segments and 2046 h of flying time. The present paper outlines the program and describes the common methodology used in these studies, which are then presented in detail in the four subsequent papers. The sixth paper offers a synthesis of this work, reviewing the major causes of flight crew fatigue and making specific suggestions about ways to manage it in different operations.

IN 1980, IN RESPONSE to a request from Congress, NASA-Ames Research Center, Moffett Field, CA, developed a research program on flight crew fatigue. A workshop was held (30) at which representatives from the scientific community, airline pilots, and airline management concluded that fatigue in air transport operations constituted a potential safety problem of uncertain magnitude. A survey of confidential reports to NASA's Aviation Safety Reporting System indicated that about one-fifth of all incidents involved factors related directly or indirectly to fatigue (23). A review of the scientific literature emphasized the potential effects of sleep loss and circadian rhythm disruption on pilot performance (19). From these initial activities it became clear that, although there was already some potentially applicable information in the scientific literature, it was not readily accessible to the aviation community, regulatory authorities, and the flying public. Further, this information came primarily from laboratory studies. There was no comprehensive work on the effects of real flight operations on sleep, circadian rhythms, and subjective fatigue, or on the consequences for cockpit performance. To redress this situation, four observational field studies were undertaken in which flight crews were monitored before, during, and after a scheduled line of flying. The papers in the present series report the findings from these studies. The operations examined were as follows.

1) Short-haul commercial air transport operations on the east coast of the U.S. (DC-9 or Boeing-737 aircraft). The goal of this study was to examine the most challenging 3–4 d trips being flown by two-person crews, with specific features including early report times and long duty days.
2) Commercial helicopter air transport operations from Aberdeen, Scotland, to service rigs in the North Sea oil fields (Aerospatiale Super Puma; Aerospatiale Tiger; Bell 214 ST; or Boeing Vertol BV234 aircraft.) The two-person crews were operating 4–5 d trips. These studies were conducted in collaboration with the Medical Department of the United Kingdom Civil Aviation Authority. Both the short-haul fixed-wing and helicopter operations involved predominantly daytime flying, with multiple flight segments per day, and crossing no more than one time zone in 24 h.
3) Commercial overnight cargo operations in the central and eastern U.S. (Boeing-727 aircraft). In these operations, three-person crews flew multiple flight segments primarily at night, and crossed no more than one time zone in 24 h. The two trip patterns studied lasted 8 d and included one 45-h break from duty that interrupted successive nights of flying.
4) Four different commercial long-haul trip patterns with three-person crews flying Boeing 747–100/200 aircraft. A 4-d round trip from the west coast of the U.S. to Auckland, New Zealand, was selected as a primarily north-south trip, involving long over-water flights but with minimal time zone crossings. A 7-d round trip from the east coast of the U.S. to Bombay, India, was selected as an example of an eastward outbound trip. A 9-d round trip from the west coast of the U.S. to Singapore, which included multiple trans-Pacific flights, was selected as a westward outbound trip. An 8-d trip pattern was also studied which included 6 transatlantic flights (from the west coast of the U.S. to London and return).

In each of these different operating environments, the

From the Fatigue Countermeasures Program, NASA-Ames Research Center, Moffett Field, CA; San Jose State University Foundation (P. H. Gander); Boeing Commercial Airplane Group (R. C. Graeber); NASA-Ames Research Center (L. J. Connell, M. R. Rosekind); and Sterling Software, Inc. (K. B. Gregory, D. L. Miller).
Address reprint requests to: Philippa H. Gander, Ph.D., who is currently a professorial research fellow in the Department of Public Health, Otago University at Wellington School of Medicine, P.O. Box 7343, Wellington South, New Zealand.

same measures were taken to assess the effects of the flight duties on sleep quantity and quality, circadian rhythms, and subjective fatigue and mood. It should be noted that no objective measures of performance were collected in the four field studies described in these papers. In addition, crewmembers completed demographic and lifestyle questionnaires and four personality inventories in an attempt to identify individual attributes that might influence how they adapt to operational demands. Detailed information on operational events was gathered by cockpit observers who accompanied participating crews throughout each trip.

These studies provide an unprecedented amount of information about fatigue in aviation operations. Field studies on this scale are rare because they require extensive cooperation and long-term financial and logistical support. They were made possible by the exceptional interest and dedication of individual flight crewmembers, their union representatives, airline management, the Federal Aviation Administration (FAA), by the ongoing commitment of NASA management to the program, and by the outstanding efforts of the many people who have been members of the NASA Fatigue and Jet-Lag program.

METHODS

Subject Recruitment and Confidentiality

A common approach and set of core measurements were developed and used in all of the fatigue field studies. For the short-haul fixed-wing, overnight cargo, and long-haul studies, which were all carried out with U.S. carriers, crewmember participation was solicited as follows. Once agreement had been obtained from the respective airline management and pilot representatives, letters and brochures were distributed at the selected domicile(s). These described the reasons for doing the research and outlined what would be involved if a crewmember decided to participate. The studies were reveiwed by the Ames Research Center Human Use Committee which classified them as exempt from further requirements since crewmembers were being observed in the course of their normal activities.

In the operations studied, crewmembers bid for monthly trip schedules which were then allocated on the basis of seniority. Members of the NASA research team received the monthly schedules in advance and selected particular trips for study. Crewmembers who were allocated these trips were subsequently contacted by telephone to solicit their participation in the study. This procedure was intended to minimize the potential bias inherent in an open call for volunteers. In the study of overnight cargo operations, crewmembers sometimes knew ahead of time which trips were being studied, which may have influenced their choice of schedules.

The helicopter study involved crews from four British commercial helicopter companies. Each company distributed a joint Civil Aviation Authority/NASA letter explaining the study and calling for volunteers. The response of pilots to this letter was universally positive, and the research team was therefore able to select the longest trips being flown at times when the cockpit observers were available to accompany crews.

Confidentiality was a major consideration in the design of the studies and the corresponding databases, both to safeguard the volunteer participants and to encourage honesty in reporting. All data and information pertaining to a crewmember were identified only by a four-digit ID number. No records were kept which linked the names of crewmembers with their ID numbers. The only way to contact an individual subsequently, e.g., to clarify or complete data, was to broadcast a request for the person with the required ID number to contact the NASA researchers. Thus any subsequent contact was also voluntary. In addition, trips were coded in the databases by month, not by day or trip number. About 85% of crewmembers approached agreed to participate, and confidentiality was not a reason cited for refusal by those who declined.

As an incentive for participating, U.S. crewmembers had the opportunity to review and discuss their own data. In addition, they received a NASA certificate of appreciation and could request passes to a shuttle launch at Kennedy Space Center. No financial incentives were offered.

Physiological Data

Crewmembers were monitored for up to 4 d prior to a scheduled trip, during the trip, and for up to 4 d after the trip. Throughout their participation in the study, they wore a Vitalog PMS-8 biomedical monitor (Vitalog Corp., Redwood City, CA). Every 2 min, this device recorded activity of the non-dominant wrist (from a watch-sized omnidirectional array of mercury switches), average heart rate (r-wave detector), and rectal temperature. The activity and heart rate data were used to cross-check self-reports of sleep timing, and were investigated as possible indicators of sleep quality. For each subject, mean activity, heart rate, and temperature during each sleep episode were calculated from 20 min after the reported sleep onset time until 10 min before the reported wakeup time. This trimming was adopted, after careful examination of many data sets, in order to minimize contamination of the estimates of mean levels during sleep by the comparatively high values which occur immediately before and after sleep. The variability in activity, heart rate, and temperature during sleep was estimated as the standard deviation of the raw scores for each sleep episode for each subject. In the short-haul fixed-wing study, heart rate during different phases of flight was also examined as a physiological indicator of the associated task demands.

In keeping with current convention, the rhythm of rectal temperature was taken as a marker for the daily cycle of the circadian clock. However, the measured rhythm reflects not only the circadian variation in temperature, but also shorter-term fluctuations (so-called masking) associated with changes in the level of physical activity, posture, and sleep. To help correct for the effects of masking on estimates of the phase and amplitude of the circadian cycle, a constant (0.28°C) was added to the raw temperature data for each subject whenever he or she was asleep. This was based on the 0.28°C difference between the temperature rhythm during sleep and wake that is observed when people live in time isolation and

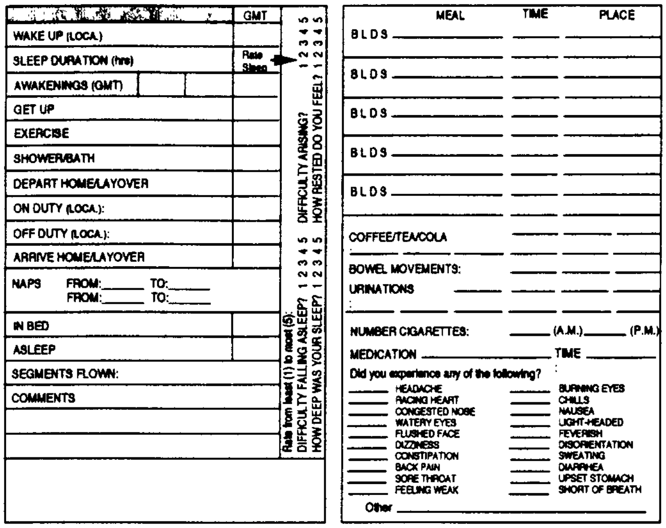

Fig. 1. Example of the pages that crewmembers completed each day to document the events of the day. The logbook was modified for the overnight cargo and long-haul studies to allow for recording of two sleep episodes per 24 h. All data were collected on Greenwich Mean Time.

adopt a sleep/wake pattern that has a periodicity different to that of the temperature rhythm (42). The effects of this mathematical "unmasking" procedure on circadian phase estimation are described in detail in reference 11.

Sleep, Subjective Fatigue, and Mood

Throughout their participation in the study, crewmembers documented their daily activities in a log book **(Fig. 1)**. These included: the timing of duty, exercise, and showers or baths; consumption of food, caffeine, and alcohol; the timing of bowel movements and urination; and the occurrence of medical symptoms and use of medications.

As soon as possible after waking up from a sleep episode, crewmembers noted in the log book the times of going to bed, falling asleep, waking up and getting up, together with the sleep duration (excluding the amount of time spent in bed awake), and the number and timing of any periods of wakefulness that they could recall during the time in bed. The quality of each sleep episode was rated from 1 (least) to 5 (most) on the questions: Difficulty falling asleep?; How deep was your sleep?; Difficulty rising?; How rested do you feel? These scores were converted so that higher values indicated better sleep, and added together to give an overall sleep rating. The timing of naps was also recorded.

Subjective sleep data can be discrepant from physiological sleep measures obtained from polygraphic recordings. Long-haul flight crews may be better able to estimate their sleep duration than the general population (5). A NASA-coordinated study (14), which measured the subjective and objective sleep and sleepiness of 56 long-haul crewmembers before and after the first segment of an international trip, found that they had a 95% probability of correctly estimating their objective sleep duration to within 30 min. However, they were less reliable at estimating sleep latency. The longer they took to fall asleep, the more they tended to overestimate how long it took. It is not known whether flight crews in other operations are able to assess their sleep more accurately than the general population. The level of internal consistency among the subjective sleep measures used in the fatigue field studies was examined in the data from the short-haul fixed-wing study (10). Longer sleep latencies were correlated with reports of greater difficulty falling asleep ($r = 0.46$, $p < 0.01$) and shorter sleep durations ($r = 0.20$, $p < 0.01$). Longer sleep durations were correlated with less difficulty falling asleep ($r = 0.22$, $p < 0.01$), deeper sleep ($r = 0.14$, $p < 0.05$), feeling more rested on awakening ($r = 0.22$, $p < 0.01$), and better overall sleep quality ratings ($r = 0.26$, $p < 0.01$). Overall, the changes in the subjective sleep measures on trips were large and consistent with the different duty demands in each type of operation.

Every 2 h while they were awake, crewmembers rated their subjective fatigue on a 10 cm line ranging from most alert to most drowsy **(Fig. 2)**. This measure has previously been shown to exhibit circadian rhythmicity in the presence or absence of environmental synchroniz-

Day ______

GMT ______ Leg/LO ______	not at all	a little	moderately	quite a bit	extremely
active	0	1	2	3	4
vigilant	0	1	2	3	4
annoyed	0	1	2	3	4
carefree	0	1	2	3	4
cheerful	0	1	2	3	4
considerate	0	1	2	3	4
alert	0	1	2	3	4
dependable	0	1	2	3	4
sleepy	0	1	2	3	4
dull	0	1	2	3	4
efficient	0	1	2	3	4
friendly	0	1	2	3	4
full of pep	0	1	2	3	4
grouchy	0	1	2	3	4
happy	0	1	2	3	4
jittery	0	1	2	3	4
kind	0	1	2	3	4
lively	0	1	2	3	4
pleasant	0	1	2	3	4
relaxed	0	1	2	3	4
forgetful	0	1	2	3	4
sluggish	0	1	2	3	4
tense	0	1	2	3	4
clear thinking	0	1	2	3	4
tired	0	1	2	3	4
hard working	0	1	2	3	4

MOST DROWSY

MOST ALERT

Fig. 2. Example of the mood adjective checklist and the visual analog scale for subjective fatigue rating. These were completed every 2 h while crewmembers were awake.

ers (27,42). Each time that they rated their fatigue, they also completed the 26-adjective checklist mood scale developed by the Naval Health Research Center (28). This scale has previously been shown to exhibit circadian rhythmicity and to be sensitive to sleep loss (29,34).

Individual Attributes

All crewmembers completed a background questionnaire compiled to obtain information on demographic and lifestyle variables, sleep and nutritional habits. They also completed three personality inventories and the circadian-type questionnaire of Horne and Ostberg (20).

The Personal Attributes Questionnaire (40) includes two scales, "instrumentality" and "expressiveness", which have both been found to correlate with check airman ratings of flight crew performance (15). Individuals scoring high in both scales are also reported to be more effective in group problem solving situations (35).

The Work and Family Orientation Questionnaire was designed to measure achievement motivation and attitudes toward family and career (16). High scores on the "work" and "mastery" scales, combined with a low score on the "competitiveness" scale, have been reported to be associated with highest attainment in groups of scientists, students, and businessmen (41).

The Eysenck Personality Inventory (7) includes two scales, "extroversion" and "neuroticism" which have been related to individual differences in circadian rhythms. There is some evidence that people scoring high on these two scales may adjust more rapidly to time-zone and schedule changes (4,12).

The circadian type questionnaire of Horne and Ostberg (20), quantifies the anecdotal distinction between "morning-types" and "evening-types." The extreme types identified by the questionnaire apparently differ in sleep timing and the time of day of the circadian temperature minimum. Some studies also indicate that evening types may adapt better to shift work and time zone changes (2,3,8,11,13,17,18,21,24,39).

Cockpit Observations

In the short-haul fixed-wing, overnight cargo, and long-haul field studies, all crews were accompanied throughout the trip by a NASA cockpit observer who held at least a private pilot's license and was familiar with air transport operations. In the helicopter field study, most crews were accompanied by a cockpit observer who was an applied psychologist familiar with helicopter operations, but not a pilot. The observers completed a log of significant operational events **(Fig. 3)** for each segment flown. They also aided crewmembers in the use and care of study equipment, and showed interested crewmembers their own physiological data during downloading of this data from the Vitalog monitor to a microcomputer.

Data Management and Analysis

For each field study, all data were entered into a relational database (Relational Information Management: NASA Contract NASA-14700). Different data types were separated into different relations, with all data for each crewmember indexed by a unique four-digit code. This organization facilitated comparative analysis among the databases, (i.e., among different types of flight operations).

Data were accessed using the S-Plus (Statistical Sciences Inc., Seattle, WA) package which provides an interactive programming environment for data processing, analysis, and graphics. S-Plus was used for primarily for preliminary data analyses and to produce data files in appropriate formats for the BMDP (University of California, Los Angeles) and ANOVA (analysis of variance; University of California, San Diego) statistical packages.

Additional Field Studies

In addition to these field studies, the NASA-Ames Fatigue and Jet-Lag Program has undertaken a variety of other studies addressing the issue of fatigue in flight operations (38). The same measures were collected in a study of the adjustment of sleep and the circadian temperature rhythm in nine Royal Norwegian Air Force volunteers operating P-3 Orion aircraft during westward and eastward flights across nine time zones. Crewmembers flew from Andoya, Norway, via an overnight layover in Brunswick, ME, to Moffett Field, CA. After at least 5 d in simulator training they undertook the return journey to Andoya. Adjustment was slower after the return eastward flight than after the outbound westward flight. The temperature rhythm of one crewmember apparently adjusted to the 9 h eastward time zone change by undergoing a reciprocal 15 h delay. More extraverted crewmembers showed larger delays of the temperature rhythm after 5 d at Moffett Field. The findings from this study are described in detail in reference 12.

An international cooperative study was conducted to better understand the effects of commercial long-haul operations on flight crew sleep. The crews that took part came from four different airlines and were based either in San Francisco, Tokyo, London, or Frankfurt. Crewmembers had their sleep and daytime sleepiness recorded polygraphically in a sleep laboratory before departing for a scheduled trip. The first flight segment of the trip crossed either 8–9 time zones westward (Frankfurt-based or London-based crews to San Francisco, San Francisco-based crews to Tokyo) or 8 time zones eastward (Tokyo-based crews to San Francisco, San Francisco-based crews to London). During the first layover, the sleep and daytime sleepiness of crews was again recorded polygraphically in a local sleep laboratory. Sleep disruption was greater after eastward than after westward flights. There was also some evidence that, after an eastward flight crossing eight time zones, morning types were more sleepy during the day than evening types. The findings from this study are described in detail in reference 14.

To address the issue of age-related changes in circadian rhythms and sleep, a meta-analysis was carried out on combined data from all the fixed-wing commercial field studies together with identical measurements from military flight crews in a number of different types of fixed-wing operations (a total of 205 crewmembers aged 20–60, of whom 91 gave complete baseline physiological data). Older crewmembers were more morning-type,

COCKPIT OBSERVER LOG

MONTH/YEAR 8 / 83 DAY 3 of 4 LEG 3 of 5

ORIG/DEST PIT/MSY EQPT DC9-7 sch pax X sch cargo ___ (circle if) other ___

CAPT ID 1624 F/O ID 4523 S/O ID —
(circle ~~pilot~~ flying this leg)
(underline if smoker)

BLOCK/FLIGHT TIMES		OUT/OFF		ON/IN
sched	1330	—	—	1547
act	1329	1334	1527	1530

DEPARTURE

RUNWAY 14 ROUTING: routine/non-routine (describe:)

ATIS/WX: vfr/ifr (if IFR, give wx:)

LIGHTING CONDX: dawn/day/dusk/night TOC 1405

COMMENTS
F/O late to A/C from term
No computerized Flt plan — not attached to 447 paperwork as should be for this long a trip

ENROUTE

ROUTING: routine/nonroutine (describe:)

LIGHTING CONDX: dawn/day/dusk/night

CRUISE ALT 350 TURB L/LC/M/MC/S/E/O/I/C

FLIGHT DECK COMFORT good/poor (describe:)

COMMENTS

COCKPIT OBSERVER LOG

ARRIVAL

ROUTING: routine/non-routine (describe:)

TOD 1507 GEAR 1523 ON ___ Rwy 10

ATIS/WX: vfr/ifr (if IFR, describe: 120 SCT 200 BKN 5H / 84°/73° / 3004 / 3012)

LIGHTING CONDX: dawn/day/dusk/night

APPROACH: ils/loc/vor/ndb/contact/circling/vis

COMMENTS 1522: Following slow PSA DC-9 had to reduce to 210 IAS
1527 Wake turb. over threshold due to slow DC-9 ahead of us & sudden add power

SUNRISE — SUNSET —

FA 11 FA 11

MEAL(req/rcvd) 0 / 1 all eat — leftover pax meal

EQUIP INOP: / /

COMMENTS
1435 Meal = fresh fruit + quiche + sausage
1530 Crew meal on ramp — sub sandwiches chips and apples
Then CAPT & F/O exit to term

DIVERSION

___ CHECK IF SIGNIFICANT COMMENTS

Fig. 3. Example of the cockpit observer log. One such report was completed for every segment flown.

and their pretrip baseline temperature rhythms were of lower amplitude than those of younger crewmembers. Among crewmembers flying long-haul operations, those aged 50–60 averaged 3.5 times more sleep loss per duty day than those aged 20–30. The findings from this study are described in detail in reference 13.

DISCUSSION

The primary objective of the four fatigue field studies was to measure the extent of fatigue in different types of flight operations, and to better understand the factors producing it. To ensure that data were as representative as possible, data gathering procedures were designed to cause minimum disturbance to the normal flow of flight operations, and crewmembers were instructed to continue their usual behavior. The strength of observational field studies is that they document real-world behavior as faithfully as possible. This gives them face-validity with the operational community. Their major weakness is that, although they may indicate correlations between different factors, they cannot investigate cause and effect. This requires controlling some factors while systematically varying others. Thus, observational field studies and controlled laboratory studies are complementary. For this reason, we have drawn heavily on the scientific literature to interpret the findings from these field studies. Particular emphasis was placed on sleep changes and circadian disruption because of the extensive scientific literature linking these physiological factors to degradation of alertness and performance (e.g., 1,6,25,26). In these four studies, no attempt was made to measure cockpit performance. More recent studies have included measures designed to probe the functional capability of crewmembers (37).

Simulator studies offer a useful compromise between operational realism and experimental control. An early study by Klein and colleagues showed circadian variation in simulator performance, and greater performance disruption after eastward vs. westward transmeridian flights (22). As part of the NASA-Ames Fatigue and Jet-Lag Program, a simulator study was conducted in which two-person short-haul crews flew a simulator scenario either as the first leg prior to a scheduled short-haul trip or as the final leg after a 3-d scheduled short-haul trip (9). The crews who had flown together out-performed the crews who had not flown together in every performance category. This was attributed to their improved crew coordination. The fatigue measures used did not permit a definitive statement about possible differences in fatigue between the two groups.

The four fatigue field studies are distinctive because of the broad diversity of measures that were collected. Large individual variability was observed in most measures. Therefore, to identify duty-induced changes, within-subjects comparisons of pretrip, trip, and posttrip values were the analytical technique of choice. A unique aspect of these studies is that the same measures were collected in different operational settings, which permits comparisons of the fatigue induced by different kinds of operational demands. This work thus provides a more comprehensive picture of fatigue in flight operations. The following four papers describe in detail the results and implications of the individual studies. The final paper provides comparative analyses and an integrated overview of the findings.

ACKNOWLEDGMENTS

The authors are deeply indebted to Drs. John Lauber, Charles Billings, and Clay Foushee, who founded the NASA Fatigue and Jet-Lag Program and made substantial contributions to this work. Particular thanks are due to Drs. Charles Billings and David Dinges who provided erudite reviews of all six papers, as well as being invaluable mentors and colleagues over the years.

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Flight Crew Fatigue II: Short-Haul Fixed-Wing Air Transport Operations

PHILIPPA H. GANDER, PH.D., KEVIN B. GREGORY, B.S.,
R. CURTIS GRAEBER, PH.D., LINDA J. CONNELL, M.A.,
DONNA L. MILLER, B.A., AND MARK R. ROSEKIND, PH.D.

GANDER PH, GREGORY KB, GRAEBER RC, CONNELL LJ, MILLER DL, ROSEKIND MR. *Flight crew fatigue II: short-haul fixed-wing air transport operations.* **Aviat Space Environ Med 1998; 69(9,Suppl.): B8–15.**

We monitored 74 crewmembers before, during, and after 3–4-d commercial short-haul trips crossing no more than one time zone per 24 h. The average duty day lasted 10.6 duty hours, with 4.5 flight hours and 5.5 flights. On trips, crewmembers slept less, woke earlier, and reported having more difficulty falling asleep, with lighter, less restful sleep than pretrip. The consumption of caffeine, alcohol, and snacks increased on trip days, as did reports of headaches, congested nose, and back pain. The study suggests the following ways of reducing fatigue during these operations: base the duration of rest periods on duty hours as well as flight hours; avoid scheduling rest periods progressively earlier across a trip; minimize early duty report times; and inform crewmembers about strategic use of caffeine and alternatives to alcohol for relaxing before sleep.

IN THE 1980's, the Fatigue Countermeasures Program at NASA-Ames conducted a series of field studies to assess flight crew fatigue in a variety of aviation environments. The first of these studies looked at commercial short-haul air transport operations. This environment is characterized by predominantly daytime flying with multiple flight segments crossing few, if any, time zones per day. The schedules were thus expected to cause minimal disruption to the circadian clock, because they allowed crewmembers to sleep during local night and did not require adaptation to new time zones. In this respect, they were viewed as a type of baseline condition against which to compare the subsequent studies of operations involving night work (overnight cargo) and irregular shift work with transmeridian flying (long-haul operations). However, short-haul operations also have specific characteristics which have been identified as potential causes of fatigue, namely long duty days with multiple flight segments and relatively long periods on the ground between flights.

Since take-off and landing are the phases of flight with the highest workload and potential for accident (15), multiple take-offs and landings in a day might be expected to have cumulative effects on fatigue and performance. Ruffell-Smith (21) reported increases in heart rate during take-off, approach, and landing of captains flying commercial Trident aircraft on selected short-haul flights. On this basis, he recommended that the number of daily flight segments should be included as a factor in the design of flight crew schedules. In a preliminary study of the effects of fatigue on flying proficiency (with one subject), Howitt et al. (11) reported behavioral observations indicating that fatigue produced by repeated flights on the same day was characterized by boredom and a lack of concern about maintaining precision on instruments.

Flying several multi-segment duty days consecutively might also be expected to have cumulative effects on fatigue and performance. Klein et al. (12) monitored physiological indices of acute stress in 11 B-737 crews across two different 3-d trips involving either a 0600–1400 hours or a 1200–2300 hours schedule. There was no evidence for cumulative effects of successive days of flying on in-flight increases in pulse and respiration rates, or on increases in urinary concentrations of catecholamines and 17-OHCS during duty days.

If long duty days and short nighttime layovers reduce the amount of sleep that crewmembers are able to obtain on trip nights, then cumulative effects on alertness and performance would be expected. In the laboratory, reducing sleep by as little as 1 h per night increases daytime sleepiness, and the effects of successive nights of reduced sleep accumulate (4,5). Reducing sleep by 2 h per night can impair alertness and performance, and causes changes in sleep architecture (shorter sleep latencies, deeper sleep, and fewer awakenings) which signal insufficient sleep (5).

Currently, Federal Aviation Regulations (FARs), which are in the process of being revised, specify scheduled rest times according to the number of hours flown in the preceding duty day. These rest times can be reduced when unforeseen circumstances arise that are beyond the company's control (aircraft malfunctions, adverse

From the Fatigue Countermeasures Program, NASA-Ames Research Center, Moffett Field, CA; San Jose State University Foundation (P. H. Gander); and Sterling Software, Inc. (K. B. Gregory, D. L. Miller); Boeing Commercial Airplane Group (R. C. Graeber); and NASA-Ames Research Center (L. J. Connell, M. R. Rosekind).

Address reprint requests to: Philippa H. Gander, Ph.D., who is currently a professorial research fellow in the Department of Public Health, Otago University at Wellington School of Medicine, P.O. Box 7343, Wellington South, New Zealand.

TABLE I. FLIGHT AND REST TIME REGULATIONS FOR DOMESTIC OPERATIONS.

Flight	Scheduled Rest	Can Be Reduced To	Compensatory Next Rest Period
<8	9 h	8 h	10 h
8–9	10 h	8 h	11 h
>9	11 h	9 h	12 h

weather, etc). In such cases, a mandated longer rest period must begin within 16 h after the reduced rest period. The requirements for Part 121 domestic operations (FAR 121.47), which governed the short-haul operations studied, are summarized in **Table I**.

There is currently no allowance made for the time of day when duty takes place. The rest time required by the FARs begins when a crewmember comes off duty and ends when he or she goes back on duty (i.e., it can include the time for traveling to and from home or a layover hotel). The FARs serve as guidelines within which individual companies decide their own scheduling policies by negotiation between management and pilots.

Two commercial airlines participated in the field study of fatigue in short-haul fixed-wing operations. The most challenging 3–4 d trips being flown by these companies were selected for study from the monthly bid packages. Most flights remained in the eastern U.S., but some crossed one time zone to central U.S.. All trips included considerable time in high traffic-density airspace.

METHODS

The 37 captains and 37 first officers (all male) who volunteered to participate were flying B-737 or DC-9 aircraft. They were monitored before, during, and after the trips summarized in **Fig. 1**. Between consecutive duty days, crews stayed in en-route layover hotels. Data were collected across all seasons of the year and were recorded on Greenwich Mean Time (GMT). They were converted to local time where necessary in the analyses (Eastern Standard Time, EST = GMT-5 h; or Eastern Daylight Time, EDT = GMT-4 h).

Characteristics of the trips are summarized in **Table II**. Data for duty times and layover durations were taken from the daily logbooks kept by crewmembers. Dáta for flight hours, number of segments, and segment duration were from the cockpit observer logs (9).

As expected, the number of flight hours per day was less than the number of duty hours per day. This difference was significant (matched pairs t-test, $t = -58.46$, $p < 0.0001$). About one third (32%) of all duty days were longer than 12 h. The mean rest period reported by crewmembers in their daily logs (12.5 h) was shorter than the time from last wheels-on at the end of one duty day to first wheels-off at the beginning of the next duty day (14.0 h; matched pairs t-test, $t = -17.52$, $p < 0.0001$). **Fig. 2** illustrates that, on average, duty days began and ended progressively earlier across trips. Two-way ANOVAs (trip-type by days-of-trip) revealed that this trend was significant for on-duty times ($F = 3.24$, $0.05 > p > 0.01$) and for off-duty times ($F = 7.75$, $p < 0.001$).

To be included in the analyses, crewmembers had to have provided complete logbook data for at least one pretrip day, all trip days, and at least one posttrip day. There were 44 crewmembers who provided sufficient data, including 11 for whom data from the second and third days posttrip were used as baseline. Their average age was 43.0 yr (SD ± 7.7) and they flew an average of 70.2 h (SD ± 9.9) per month in all categories of aviation. They had an average of 17.1 yr (SD ± 6.6) of airline experience. Unless otherwise stated, all analyses of variance were within subjects. For t-tests, where a Levene's test revealed unequal variances, the separate t-test value was taken. Otherwise, the pooled t-test value was taken.

In addition to the logbook fatigue measures, changes in heart rate during different phases of flight were also examined. Since the physiological monitor recorded only 2-min averages of the r-wave intervals, it was not possible to examine beat by beat variability. The heart rate during take-off was taken as the average of three consecutive 2-min intervals, with actual take-off occurring in the first 2-min interval. The heart rate during mid-cruise was taken as the average of five consecutive 2-min intervals centered between top-of-climb and top-of-descent. The heart rate during descent was taken as the average of five consecutive 2-min intervals, with touch-down occurring in the 2-min interval immediately following the 10 min defined as descent. The average heart rate during landing was taken as the average of three consecutive 2-min intervals, with touch-down occurring in the last interval. Complete heart rate data were available for 589 flight segments. For each flight segment for each crewmember, the heart rate during mid-cruise was subtracted from the heart rates during take-off, descent, and landing. These differences were then expressed as percentages of the heart rate during mid-cruise. The percentage change in heart rate was chosen as a metric to minimize inter-subject and time-of-day variability.

RESULTS

Sleep

Table III compares the average sleep measures on pretrip, trip, and posttrip nights. Sleep latency was calculated as the difference between the reported times of going to bed and falling asleep. Scores on the four sleep quality questions, rated from 1 (least) to 5 (most), have been converted so that higher values indicate better sleep, and combined to give the overall sleep rating. Heart rate and activity data during each sleep episode have been trimmed to include values from 20 min after the reported sleep onset time until 10 min before the reported wakeup time (9). Only 11 of 44 crewmembers provided sufficient physiological data for these analyses. In this first field study, most data loss occurred because of technical or logistical difficulties. The probabilities in Table III indicate values for pretrip/trip/posttrip comparisons in one-way analyses of variance (ANOVA) with subjects treated as a random variable. When an ANOVA was significant, pretrip, trip, and posttrip values were compared by post hoc t-tests. All the comparisons described below were significant at least at $p < 0.05$.

On trips, crewmembers slept less, awoke earlier and reported having more difficulty falling asleep, with

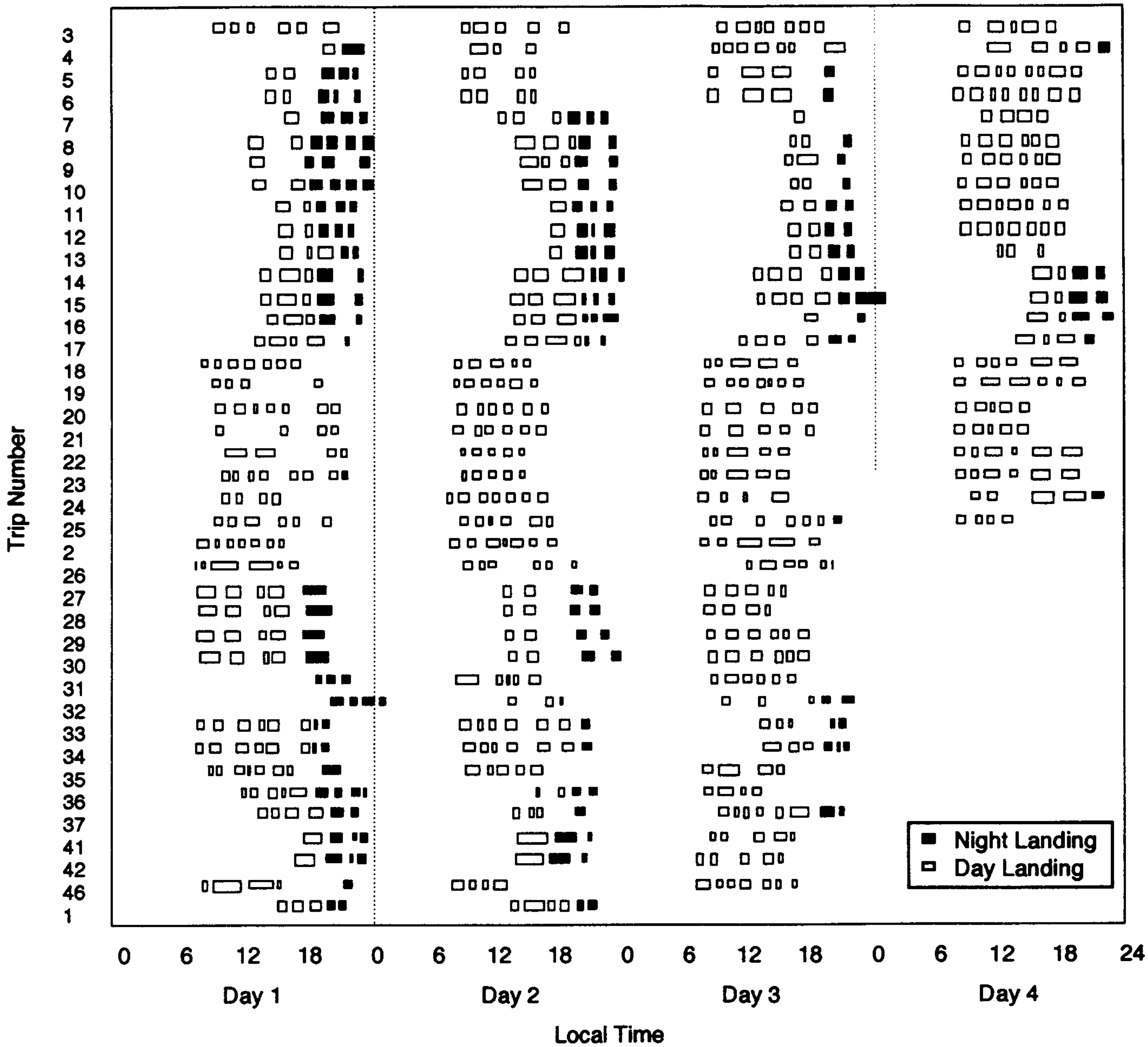

Fig. 1. Sequence of flight segments for each of the trips studied (23 4-d trips; 16 3-d trips; 1 preliminary 2-d trip which was not included in the analyses). Trip numbers indicate the order in which trips were studied. Open boxes: segments landing in daylight. Black boxes: segments landing at night.

lighter, less restful sleep, and poorer overall sleep quality, than either pretrip or posttrip. The analyses in Table III include the final sleep episode prior to the trip as a pretrip sleep episode. However, crewmembers were frequently required to get up earlier than usual to report for duty on the first day of the trip. Considering this sleep episode as a trip sleep suggests that, in addition to the differences in Table III, crewmembers also took longer to fall asleep on trip nights (mean 24.7 min) than pretrip (mean 15.7, $F = 7.75$, $p < 0.001$). The total sleep per 24 h calculated this way was shorter on trip days (mean 6.6 h) than either pretrip (mean 8.2 h) or posttrip (mean 7.7 h, $F = 22.55$, $p < 0.001$).

The percentage of subjects who reported sleeping or napping more than once per 24 h was particularly low on trip days (pretrip 21%, trip 7%, postrip 15%). This may be the result of long duty days and relatively short nighttime layovers (Table II). Since the total sleep per 24 h (including all sleeps and naps) on trip days was 1.6 h shorter than during pretrip, crewmembers accumulated a sleep debt across trips (**Fig. 3**). Comparing trip days to pretrip days, 67% of crewmembers averaged more than 1 h of sleep loss per 24 h, and 30% averaged more than 2 h of sleep loss. The hours of sleep lost during the trips were not regained after 2 nights of posttrip sleep (the curves in Fig. 3 do not return to zero). However, this is not unexpected since sleep loss is normally compensated by deeper rather than proportionally longer sleep (7).

Crewmembers on 3-d trips averaged significantly more sleep loss per day than did crewmembers on 4-d

TABLE II. TRIP STATISTICS.

	Mean (SD)	Minimum	Maximum
On-duty (local time)	0943 (4.19)	0500	2115
Off-duty (local time)	1930 (2.86)	0935	0130
Duty hours/day	10.63 (2.24)	2.23	15.83
Flight hours/day	4.51 (1.35)	0.83	7.48
(Duty-Flight) hours	6.13 (1.68)	0.29	10.72
# Segments/day	5.51 (1.37)	1.00	8.00
Segment duration (h)	1.07 (0.46)	0.22	2.97
Nighttime layover (h)	12.45 (2.66)	7.17	20.02

Note: Trips crossed no more than one time zone in 24 h.

TABLE III. COMPARISONS OF SLEEP MEASURES BEFORE, DURING, AND AFTER TRIPS.

	Pretrip	Trip	Posttrip	F
Sleep onset (GMT)	4.39	4.17	4.55	4.08*
Wakeup (GMT)	11.99	10.87	12.17	31.38***
Sleep latency (min)	23.50	25.60	22.73	0.32
Sleep duration (h)	7.22	6.59	7.36	6.33**
Total sleep/24 h	7.39	6.68	7.55	7.73*
Difficulty falling asleep?	4.34	3.95	4.30	4.00*
How deep was your sleep?	3.84	3.22	3.77	15.41***
Difficulty rising?	4.06	4.11	3.94	1.00
How rested do you feel?	3.47	3.08	3.42	4.07*
Sleep rating	15.70	14.34	15.42	6.24**
# Awakenings	1.20	1.15	1.14	0.29
Mean heart rate (bpm)	63.33	64.41	61.50	1.45
S.D. heart rate	6.65	7.21	7.05	0.13
Mean activity (counts/min)	1.29	1.35	1.39	0.04
S.D. activity	4.46	5.15	5.46	0.23

* $0.05 > p > 0.01$; ** $0.01 > p > 0.001$; *** $p < 0.001$.

trips (paired t-test, $t = 4.24$, $0.001 > p > 0.0001$). Part of this difference may be an artifact of the way that sleep loss was calculated. Three-day crewmembers were three times more likely to nap on the day before a trip. This napping extended their total baseline sleep beyond what they reported in the Background Questionnaire as their usual amount of home sleep (matched pairs t-test, $t = 2.41$, $0.05 > p > 0.01$), which suggests that it may have represented a strategy to cope with anticipated sleep loss. These pretrip naps inflated the estimate of baseline sleep duration, against which subsequent sleep loss was calculated. Duty days on 3-d and 4-d trips were of comparable length. However, 3-d trips included significantly more daily flight hours than did 4-d trips (two-way ANOVA, trip-type by days-of-trip; F for the trip-type comparison = 7.40, $0.01 > p > 0.001$). Thus there was less time available for napping between flight segments on 3-d trips.

Fatigue and Mood Ratings

Every 2 h while they were awake, crewmembers rated their fatigue level on a 10 cm line from "most alert" to "most drowsy." They also rated their current mood from 0 (not at all) to 4 (extremely) on 26 adjectives which were found to load on three orthogonal factors: positive affect, negative affect, and activation (8). Within subjects two-way ANOVAs (pretrip/trip/posttrip by time-of-day) were carried out to see if duty demands had a measurable effect on fatigue and mood ratings **(Table IV)**. There were 11 crewmembers who provided sufficient data for these analyses, with the ratings grouped in 4-h time bins.

Fatigue, negative affect, and activation showed significant time-of-day variation **(Fig. 4)**. However, these analyses suggests that none of the ratings changed significantly across trip days by comparison with pretrip or posttrip.

In order to include data from a larger number of crewmembers (n = 34), a one-way ANOVA, treating subjects as a random variable, was carried out to compare the final ratings of the day on pretrip, trip, and posttrip days **(Table V)**. The only significant change was that positive affect was lowest posttrip.

Caffeine and Alcohol Consumption

Caffeine was available in-flight as well as on the ground. The number of cups of caffeinated beverages,

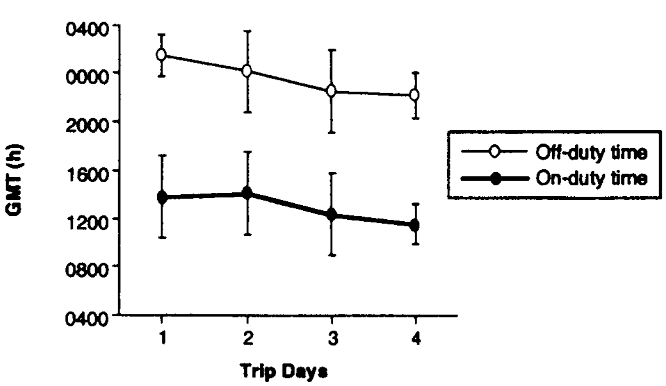

Fig. 2. Average on-duty and off-duty times across trips (vertical lines indicate standard errors).

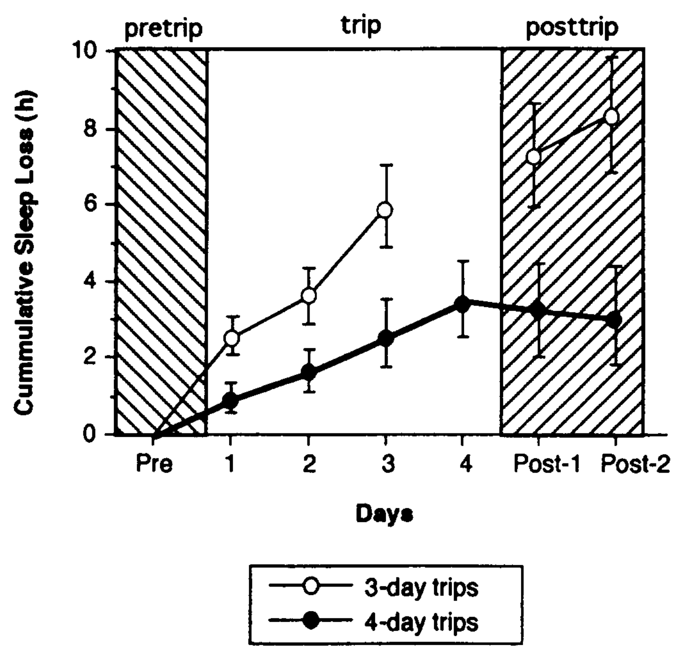

Fig. 3. Average cumulative sleep loss with respect to baseline sleep, across 3-d and 4-d trips. For each subject, his total sleep per 24 h on each trip day was subtracted from his average total sleep per 24 h on pretrip days, to give a daily measure of sleep loss. Average daily sleep loss was then calculated, and the values added across the consecutive trip days and posttrip days. Vertical lines indicate standard errors.

TABLE IV. FATIGUE AND MOOD RATINGS ACROSS PRETRIP, TRIP, AND POSTTRIP DAYS.

	F Pre/Trip/Post	F Time-of-Day	F Interaction
Fatigue	0.60	4.49*	1.31
Positive affect	1.43	1.34	0.33
Negative affect	1.25	13.90***	1.25
Activation	2.45	15.42***	1.11

* 0.05 > p > 0.01; *** p < 0.001.

TABLE V. FINAL FATIGUE AND MOOD RATINGS OF THE DAY, COMPARING PRETRIP, TRIP, AND POSTTRIP DAYS.

	Pretrip Mean (SD)	Trip Mean (SD)	Posttrip Mean (SD)	F
Fatigue	52.7 (15.0)	52.9 (12.1)	58.6 (16.7)	2.75
Positive affect	2.29 (0.62)	2.24 (0.52)	2.02 (0.70)	4.19*
Negative affect	0.79 (0.56)	0.80 (0.39)	0.88 (0.43)	0.92
Activation	1.56 (0.64)	1.75 (0.54)	1.52 (0.66)	2.71

* 0.05 > p > 0.01.

and the time of day at which they were consumed, were recorded in the daily logbook. Alcohol consumption was also indicated, with one glass of beer or wine, or one measure of spirits, counting as one serving. Since Federal Regulations prohibit the consumption of alcohol within 8 h of going on duty, it is assumed that alcohol consumption on trip days took place in the evening, after coming off duty.

Caffeine was consumed at some time during the study by 94% of the crewmembers, while alcohol was consumed by 73%. To test if duty demands had an effect on caffeine or alcohol consumption, one-way ANOVAs were performed, with subjects treated as a random variable **(Table VI)**.

Caffeine consumption increased during trips by comparison with pretrip levels (t = 3.92, p < 0.001). Alcohol consumption also increased during trips by comparison with pretrip (t = 4.55, p < 0.0001) or posttrip (t = 1.98, 0.05 > p > 0.01).

Meals and Snacks

Only one of the two participating airlines provided crew meals in flight. The time of eating and classification of meals (breakfast, lunch, dinner, snack) was recorded in the daily logbook. To test whether duty demands had an effect on the number of meals or snacks eaten per day, one-way ANOVAs were performed with subjects treated as a random variable **(Table VII)**.

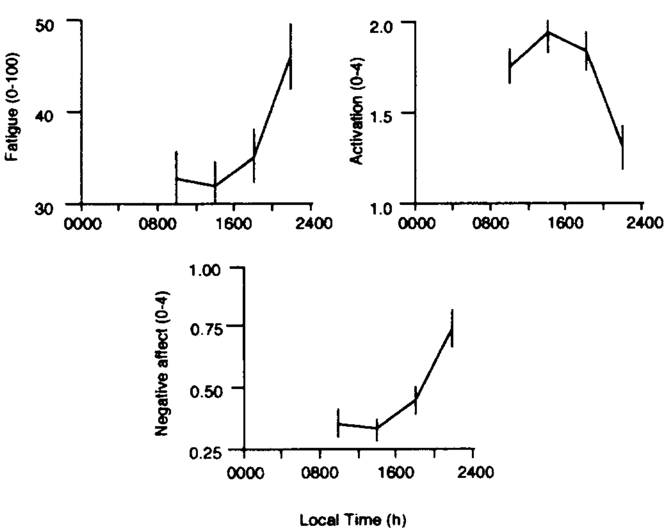

Fig. 4. Time of day variations in fatigue and mood ratings (vertical lines indicate standard errors).

More snacks were eaten on trip days than either pretrip (t = 9.30, p < 0.0001) or posttrip (t = 3.91, 0.001 > p > 0.0001). To test if the provision of crew meals affected the number of meals or snacks eaten, two-way ANOVAs (company by pre/trip/post) were performed **(Table VIII)**.

These analyses suggest that the provision of crew meals did not have a significant effect on the number of meals or snacks eaten. However they do not address the quality of the nutrition obtained.

Physical Symptoms

The logbook also contained a table for each day for noting physical symptoms (9). Some 60% of crewmembers indicated that they experienced at least one of the 20 categories of symptoms at some time during the study. The three most common symptoms were: headache (reported by 27% of crewmembers at some time during the study); congested nose (reported by 20% of crewmembers at some time during the study); and back pain (reported by 11% of crewmembers at some time during the study). The frequency of reports of each of these symptoms on pretrip, trip, and posttrip days is shown in **Table IX**. All three symptoms were reported most often on trips.

Heart Rate During Different Phases of Flight

Paired t-tests indicated significant increases in heart rate (compared with mid-cruise) during descent (t = 5.48, p < 0.0001) and landing (t = 5.46, p < 0.0001), but not during takeoff. In these operations, captains and first officers usually alternated cockpit seats, and thus responsibility for control of the aircraft, on successive flight segments. To test if changes in heart rate depended on rank (captain vs. first officer) or cockpit task (flying vs. not-flying) two-way ANOVAs were performed **(Table X)**.

During descent and landing, heart rate increased (by comparison with mid-cruise) for the crewmember flying (5.8% and 4.2%, respectively), but decreased slightly for the crewmember not flying (1.9% decrease and 0.1% decrease, respectively). During descent, the difference be-

TABLE VI. CAFFEINE AND ALCOHOL CONSUMPTION.

	Pretrip	Trip	Posttrip	F
Caffeine, servings/day	2.03	3.06	2.60	8.78***
Alcohol, servings/day	0.34	1.54	0.90	14.16***

*** p < 0.001.

TABLE VII. CONSUMPTION OF MEALS AND SNACKS.

	Pretrip	Trip	Posttrip	F
Number of meals/day	2.38	2.33	2.40	0.123
Number of snacks/day	0.17	1.33	0.73	26.17***

*** $p < 0.001$.

tween flying and non-flying conditions was greater for first officers (9.6%) than for captains (5.9%).

To test whether flight conditions affected heart rate changes, a two-way ANOVA was performed [visual flight conditions (VFR) vs. instrument flight conditions (IFR), and flying vs. not flying; **Table XI**].

During takeoff and descent, heart rate increases (by comparison with mid-cruise) were greater under IFR conditions (1.2% and 4.3%, respectively) than under VFR conditions (−0.6% and 1.6%, respectively). During descent, the difference between flying and not flying was greater under IFR conditions (11.0%) than under VFR conditions (7.2%).

DISCUSSION

This study is the first extensive documentation of sleep, circadian rhythms, and subjective fatigue during scheduled short-haul operations. On trip nights, the average sleep episode was about an hour shorter than on pretrip nights. Multiple regression analyses reported elsewhere (8) suggest that this was primarily due to long duty days, short nighttime layovers, and having to wake up over an hour earlier to report for duty. Sleep restriction caused by early on-duty times has also been reported in a study of USAF pilot instructors and students (16). Comparing the total sleep per 24 h (including naps) on trip days vs. pretrip days, 67% of crewmembers averaged more than 1 h of sleep loss on trip days, and 30% averaged more than 2 h of sleep loss. In the laboratory, 1 h of sleep loss per night produces a cumulative increase in sleepiness (4). Reducing nighttime sleep in the laboratory by more than 2 h can impair performance and cause changes in sleep architecture that indicate insufficient sleep (5). On the other hand, 12% of crewmembers reported averaging more sleep on trip nights than pretrip.

Average daily sleep loss was greater across 3-d trips than across 4-d trips. However, part of this difference may have been an artifact of the way sleep loss was calculated. Many 3-d crewmembers took a nap the day before going on duty. This nap inflated the estimate of baseline sleep duration, thereby increasing the apparent sleep loss on trip nights. The 3-day trips also included more flight hours per day than the 4-d trips. This would have limited the time available for napping on duty days.

TABLE VIII. MEALS BEFORE, DURING, AND AFTER TRIPS WITH AND WITHOUT CREW MEALS.

	F Company	F Pre/Trip/Post	F Interaction
Number of meals/day	0.65	2.03	0.13
Number of snacks/day	1.54	15.14***	0.11

*** $p < 0.001$.

TABLE IX. FREQUENCY OF REPORTS OF COMMON PHYSICAL SYMPTOMS.

Symptom	% Pretrip	% Trip	% Posttrip
Headache	32	41	27
Congested nose	26	58	16
Back pain	17	75	8

Crewmembers did not compensate for early duty report times by going to sleep earlier on trip nights. Anecdotally, they often talked about needing to "spin down" (relax) after a duty day before being able to fall asleep. There are also physiological factors which make it difficult to fall asleep earlier than usual. Sleep onset is less likely at certain phases of the circadian cycle (the so-called "wake maintenance zones"), one of which occurs shortly before the habitual bedtime (23,24). In addition, because the "biological day" dictated by the circadian clock tends to be longer than 24 h, it is easier to go to sleep later than to go to sleep earlier. Going to sleep later also means staying awake longer, which allows more time for homeostatic "sleep pressure" to build up (2,7).

In addition to sleeping less on trip days, crewmembers also reported taking longer to fall asleep, and having lighter and less restful sleep. In contrast, reducing nighttime sleep in the laboratory results in shorter sleep latencies, and deeper sleep with fewer awakenings (5). If sleep quality was indeed compromised during trips, as the subjective ratings suggest, then this would be expected to further reduce subsequent alertness and performance, in addition to the effects of sleep loss (20). Unfamiliar and/or uncomfortable layover hotel rooms could have contributed to a reduction in sleep quality, as could the consumption of alcohol close to bedtime (see below).

Subjective ratings of fatigue and mood did not change significantly on trip days by comparison with pretrip days. Fatigue and negative affect ratings varied in parallel across the day, being lowest around noon and highest in the last rating of the day. This replicates the time-of-day variation in subjective fatigue ratings reported for people living under a variety of different experimental protocols (13,14,25). Activation ratings also varied significantly across the day, as the mirror image of fatigue and negative affect, being highest around noon and lowest in the last rating of the day. Subjective fatigue and activation ratings appear to be influenced by both the circadian cycle and the time since sleep (13,14). Positive affect did not show a significant time-of-day variation.

On trip days, crewmembers consumed 1.5 times more caffeine than on pretrip days. The additional caffeine was

TABLE X. HEART RATE CHANGES: EFFECTS OF RANK AND POSITION.

Phase of Flight	F Rank	F Flying/Not-Flying	F Interaction
Take-off	0.23	0.01	0.01
Descent	2.50	172.07****	9.61**
Landing	0.40	41.72****	0.71

** $0.01 > p > 0.001$, **** $p < 0.0001$.

TABLE XI. HEART RATE CHANGES: EFFECTS OF WEATHER AND POSITION.

Phase of Flight	F VFR/IFR	F Flying?	F Interaction
Take-off	4.29*	0.16	0.31
Descent	8.22**	92.28****	3.94*
Landing	1.17	14.79****	0.07

* $0.05 > p > 0.01$, ** $0.01 > p > 0.001$, **** $p < 0.0001$.

consumed primarily shortly after wakeup (which was earlier on trips) and around the time of the mid-afternoon peak in physiological sleepiness (8). The urge to fall asleep in the afternoon would be expected to increase progressively with the sleep loss accumulating across trip days (4). Multiple regression analyses reported elsewhere (8) indicated that the earlier crewmembers went on duty, and the longer they remained on duty, the more caffeine they consumed. Caffeine can temporarily improve daytime alertness. However, consumed close to bedtime, it also has disruptive effects on sleep, including longer sleep latencies, lighter sleep, and more awakenings (3).

On trip days, crewmembers reported consuming 2.5 times as many alcoholic drinks as at home (combining pretrip and posttrip days). More alcohol was consumed after shorter duty days (8). Federal Regulations prohibit alcohol consumption within 8 h of going on duty, and it is assumed that drinking occurred after coming off duty in the evening. Alcohol consumed in close proximity to sleep causes dose-dependent changes in sleep, reducing the time taken to fall asleep but increasing the number of awakenings during sleep. It also suppresses rapid eye movement (REM) sleep in the first half of the night, leading to REM rebound in the second half of the night. Alcohol consumption and sleep restriction act synergistically to increase daytime sleepiness (3).

Crewmembers ate twice as many snacks on trip days as on pretrip and posttrip days. However, the number of meals eaten did not change. This might indicate that meals eaten on trip days were less filling. The provision of crew meals did not alter the number of meals or snacks eaten on trips. However, since meal content was not considered in these analyses, it would be premature to conclude that the provision of crew meals did not affect the quality of nutrition on trips.

Physical symptoms were reported by 60% of crewmembers at some time during the study, with the three most common symptoms being headaches, congested nose, and back pain. The incidence of reports of all three symptoms was greater on trips than at home.

During descent and landing, the responsibility of flying the aircraft produced significant increases in heart rate (over the level during mid-cruise). During descent, this effect was greater for first officers flying than for captains flying, and was exacerbated under instrument flight conditions. When instrument flight conditions prevailed during takeoff, heart rate increases were greater than under visual flight conditions. Similar effects have been observed in a wide variety of aircraft types, in line-flying, in line-training, and in simulators (1,10,11,17–19,21,22). It has been argued that these heart rate responses in experienced pilots are influenced primarily by work-related factors, rather than emotional stressors such as risk and anxiety (17–19).

In summary, the trips studied required crewmembers to wake up earlier, thereby accumulating a sleep debt which, on the basis of laboratory studies, would be expected to reduce daytime alertness and performance. They also reported poorer quality sleep on trips. The consumption of caffeine, alcohol, and snacks increased on trip days, as did reports of headaches, congested nose, and back pain. The study suggests a number of ways in which these effects of trips could be improved.

1. In the trips studied, duty days were more than twice as long (average 10.6 h) as the total duration of the flights that they included (average 4.5 h). One third of the duty days were longer than 12 h. Longer duty days were not followed by proportionally longer rest periods (8). This suggests that one way of reducing sleep loss would be to include the duration of the duty day as a factor in the determination of the duration of the subsequent rest period. Current Federal Regulations base rest requirements entirely on flight hours.
2. The scheduling practice of requiring early report times makes it more difficult for crewmembers to obtain adequate sleep, even during relatively long layovers. This is because physiological factors tend to oppose falling asleep earlier than the usual bedtime. Minimizing early duty report times would thus be expected to reduce sleep loss. In the majority of the trips studied, duty also began and ended earlier on successive trip days. Because it is difficult to fall asleep earlier than usual, this has the effect of progressively reducing the time available for sleep in each successive layover. Thus, where possible, successive duty days should begin at the same time, or progressively later.
3. The use of alcohol as a means of relaxing before sleep appears to be widespread. While a "nightcap" may make it easier to fall asleep, it can have deleterious effects on sleep quality, and may therefore adversely affect subsequent alertness and performance. Sleep on trips could probably be improved in many cases by providing crewmembers with information on alternative relaxation techniques which have been well-tested in the treatment of sleep disorders.

ACKNOWLEDGMENTS

This study was made possible by the enthusiasm and dedication of the crewmember volunteers, and the management and pilot associations of the participating airlines. Mike Baetge and Kathy Craig provided invaluable services as cockpit observers.

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Flight Crew Fatigue III: North Sea Helicopter Air Transport Operations

PHILIPPA H. GANDER, PH.D., RORY M. BARNES, M.D., KEVIN B. GREGORY, B.S., R. CURTIS GRAEBER, PH.D., LINDA J. CONNELL, M.A., AND MARK R. ROSEKIND, PH.D.

GANDER PH, BARNES RM, GREGORY KB, GRAEBER RC, CONNELL LJ, ROSEKIND MR. *Flight crew fatigue III: North Sea helicopter air transport operations*. **Aviat Space Environ Med 1998; 69(9,Suppl.):B16–25.**

We studied 32 helicopter pilots before, during, and after 4–5 d trips from Aberdeen, Scotland, to service North Sea oil rigs. On duty days, subjects awoke 1.5 h earlier than pretrip or posttrip, after having slept nearly an hour less. Subjective fatigue was greater posttrip than pretrip. By the end of trip days, fatigue was greater and mood more negative than by the end of pretrip days. During trips, daily caffeine consumption increased 42%, reports of headache doubled, reports of back pain increased 12-fold, and reports of burning eyes quadrupled. In the cockpits studied, thermal discomfort and high vibration levels were common. Subjective workload during preflight, taxi, climb, and cruise was related to the crewmembers' ratings of the quality of the aircraft systems. During descent and approach, workload was affected by weather at the landing site. During landing, it was influenced by the quality of the landing site and air traffic control. Beginning duty later, and greater attention to aircraft comfort and maintenance, should reduce fatigue in these operations.

IN THE MID-1980's, the Fatigue Countermeasures Program at NASA-Ames Research Center and the Medical Department of the United Kingdom Civil Aviation Authority undertook a field study of fatigue in helicopter crews flying support operations from Aberdeen, Scotland, to the North Sea oil fields. These operations began on August 1, 1967. By the time the fatigue study took place, Aberdeen Airport had handled more than half a million helicopter flights and there were four support companies operating about 50 helicopters, making it one of the largest helicopter operations ever undertaken. Activities include lifting, shuttling, and the carrying goods and personnel between Aberdeen and the rigs.

This environment, like the short-haul fixed-wing operations described in the previous paper (10), involved daytime flying with no time zone crossings. It was therefore expected to cause minimal disruption to the circadian clock. Like the fixed-wing operations, it included multiple flight segments in a duty day, and two-person flight crews. However, the North Sea helicopter operations involved additional factors which were seen as potential causes of fatigue. Some of the flights were of extended duration, for example, to the North Shetland Basin (**Fig. 1**), which represented a round trip of about 560 mi or 5 h flying time. The quality of landing sites was very variable, often with few alternates available, and weather conditions in the North Sea are notoriously poor. The helicopter flightdeck was a more physically stressful working environment, where poor ventilation and high levels of vibration were common (12). The large transparent areas surrounding the flight deck exposed crews to solar heating. Cold sea temperatures and severe weather often necessitated the wearing of immersion suits, and it was not uncommon for crewmembers to become uncomfortably hot (11). The helicopters also required more active control and had less sophisticated supporting automation than the fixed-wing aircraft studied.

Four commercial companies participated in the field study of fatigue in helicopter operations, which looked at the most challenging 4–5 d trips being flown out of Aberdeen. The Medical Department of the CAA also sponsored studies addressing the vibration levels in the cockpit (12), the thermal environment and its effects on body temperature (11), and workload associated with paperwork in these operations (13). The same crews and aircraft were studied, but not on the same flights.

METHODS

The 32 male pilots who volunteered to participate were flying Aerospatiale Super Puma, Aerospatiale Tiger, Bell 214 ST, or Boeing Vertol BV234 helicopters. They were monitored before, during, and after the trips* summarized in **Fig. 2**. At the end of each duty day, crews returned home to Aberdeen. There was one exception (the first day of trip three) when a hydraulic failure forced the crew to remain overnight on a rig. Data were collected during February to May 1986 (winter/spring) and

From the Fatigue Countermeasures Program, NASA-Ames Research Center, Moffett Field, CA; San Jose State University Foundation (P. H. Gander); United Kingdom Civil Aviation Authority (R. M. Barnes); Sterling Software, Inc. (K. B. Gregory); Boeing Commercial Airplane Group (R. C. Graeber); and NASA-Ames Research Center (L. J. Connell, M. R. Roeskind).

Address reprint requests to: Philippa H. Gander, Ph.D., who is currently a professorial research fellow in the Department of Public Health, Otago University at Wellington School of Medicine, P.O. Box 7343, Wellington South, New Zealand.

*For consistency with the other fatigue studies, the 4–5 d duty periods will be referred to as trips, even although the crews returned home every night.

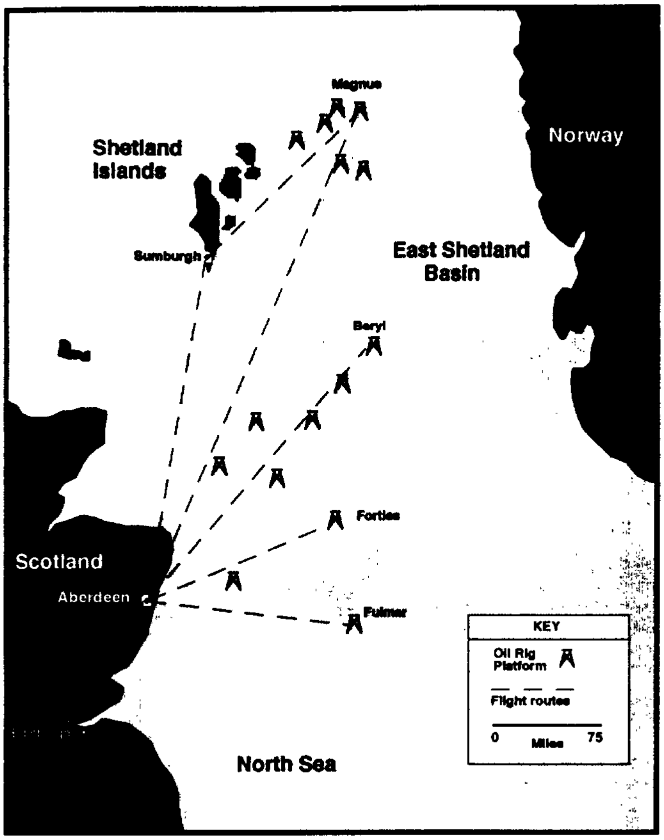


Fig. 1. The Shetland Basin, where the operations took place.

during the following July to September (summer/autumn). All times were recorded on Greenwich Mean Time (GMT). Local time was GMT in the winter and GMT + 1 in the summer. Characteristics of the trips are summarized in **Table I**. Data for duty times and layover durations were taken from the daily logbooks kept by crewmembers. Data for flight hours, number of segments, and segment duration were from the cockpit observer logs (9).

To be included in the analyses, crewmembers had to have provided logbook data for at least one pretrip day, all trip days, and at least one posttrip day. There were 22 crewmembers who provided sufficient data, including 17 who flew 4-d trips and 5 who flew 5-d trips. Their average age was 34.3 yr (SD ± 6.7 yr), and they reported an average of 8.6 yr (SD ± 4.4 yr) of flying experience, taken as the largest value from among the categories: years with the present airline; years of military experience; years of airline experience; years of general aviation experience; and other. This value probably underestimates the total years of helicopter flying experience, since half the crewmembers had some years of military experience before going into commercial aviation. Calculating experience as the sum of military and the highest other category suggested an average helicopter flight experience of 10.7 yr. Of the 22 crewmembers, 3 provided incomplete data on duty times and were therefore excluded from the statistics in Table I. Unless otherwise stated, all analyses of variance were within subjects. For *t*-tests, where a Levene's test revealed unequal variances, the separate *t*-test value was taken. Otherwise, the pooled value was taken.

In addition to the standard measures collected in the NASA fatigue studies (9), the helicopter pilots were asked to rate their workload during each phase of flight as soon as possible after the completion of that phase. The subjective measure of workload used was a modified Bedford Scale (14). This gives an assessment of the overall workload (on a scale from 1–10) without attempting to differentiate between mental, physical, and temporal loads. Pilots also rated, on a scale from one (very favorable) to five (very unfavorable), the following aspects of each flight segment: the weather conditions for landing; the particular airport, platform, or rig where the landing occurred; and (where applicable) the letdown aids and air traffic control. The functioning of the aircraft systems was rated for every segment on a scale from one (perfect) to five (useless). **Fig. 3** shows an example of the rating cards used.

RESULTS

Sleep

Table II compares the sleep measures on pretrip, trip, and posttrip nights. Sleep latency was calculated as the difference between the reported times of going to bed and falling asleep. Scores on the four sleep quality questions, rated from 1 (least) to 5 (most), have been converted so that higher values indicate better sleep, and combined to give the overall sleep rating. Heart rate, temperature, and activity data during each sleep episode have been trimmed to include values from 20 min after the reported sleep onset time until 10 min before the reported wakeup time (9). Physiological data during sleep were available for 20 subjects (63%). The probabilities in Table II indicate values for the pretrip/trip/posttrip comparisons in one-way analyses of variance (ANOVA), with subjects treated as a random variable. Where the ANOVAs indicated significant differences, post hoc *t*-tests were used to compare pretrip, trip, and posttrip values. All the comparisons discussed were significant at least at $p < 0.05$.

On trip days, subjects fell asleep earlier and woke up earlier than either pretrip or posttrip. The nighttime sleep episode was shorter, and the total sleep per 24 h (i.e., including naps) was less than either pretrip or posttrip. Sleep latencies were shorter pretrip than during trips or posttrip.

The percentage of subjects who reported sleeping or napping more than once per 24 h was relatively low on trip days (pretrip 13%, trip 21%, posttrip 35%). One reason for this is that CAA regulations prohibit napping in two-person cockpits. Since the total sleep per 24 h on trip days averaged 0.81 h less than during pretrip, crewmembers accumulated a sleep debt across trips **(Fig. 4)**. Comparing trip days to pretrip days, 50% of crewmembers averaged more than 1 h of sleep loss per 24 h, and 14% averaged more than 2 h of sleep loss. The hours of sleep lost during the trips were not regained after 2 nights of posttrip sleep. However, this is not unexpected since recovery sleep after sleep loss does not make up the number of hours of sleep lost, but is deeper than normal sleep (1,5). The cumulative sleep loss at the end of 4-d trips was not significantly differ-

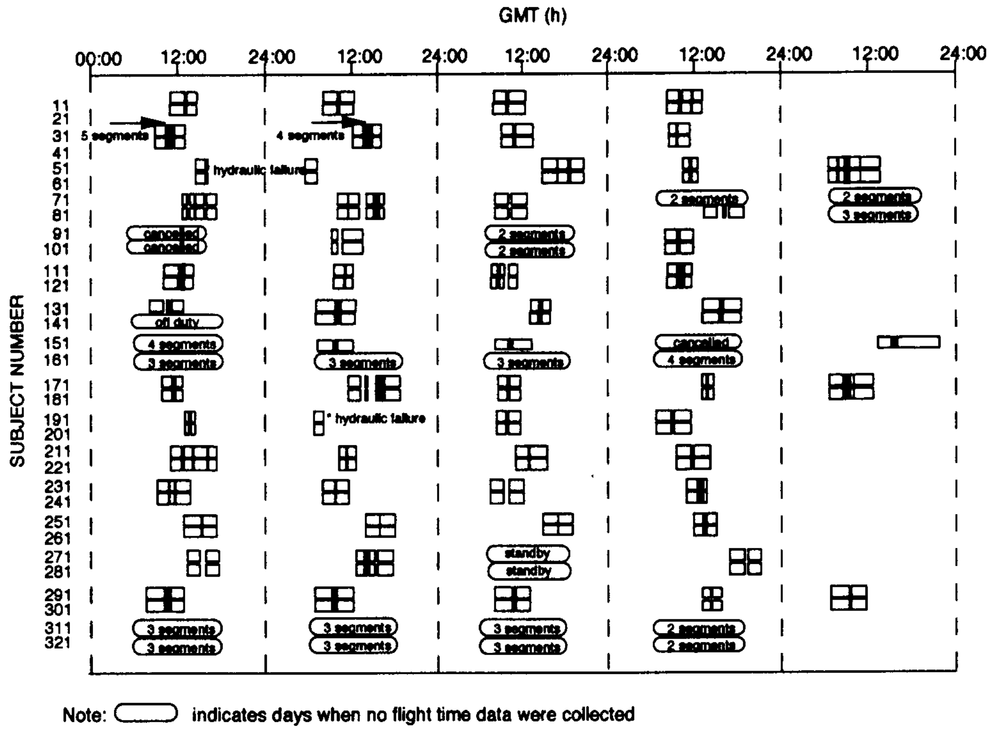


Fig. 2. Time lines of the trips studied. Open bars indicate flight segments. Shaded bars indicate multiple very short flight segments. Flight time data were unavailable for the segments in the rounded frames.

ent from that at the end of 5-d trips (2-group t-test; $t = -1.65$, $p = 0.12$).

Fatigue and Mood Ratings

Every 2 h while they were awake, subjects rated their fatigue level on a 10 cm line from "most alert" to "most drowsy." They also rated their current mood from 0 (not at all) to 4 (extremely) on 26 adjectives which have been shown to load on three orthogonal factors: positive affect, negative affect and activation (8). Within-subjects two-way ANOVAs (pretrip/trip/posttrip by time-of-day) were performed to see if duty demands had a measurable effect on fatigue and mood ratings **(Table III)**. There were 16 crewmembers who provided sufficient data for these analyses, with the ratings grouped in 4 h time-bins.

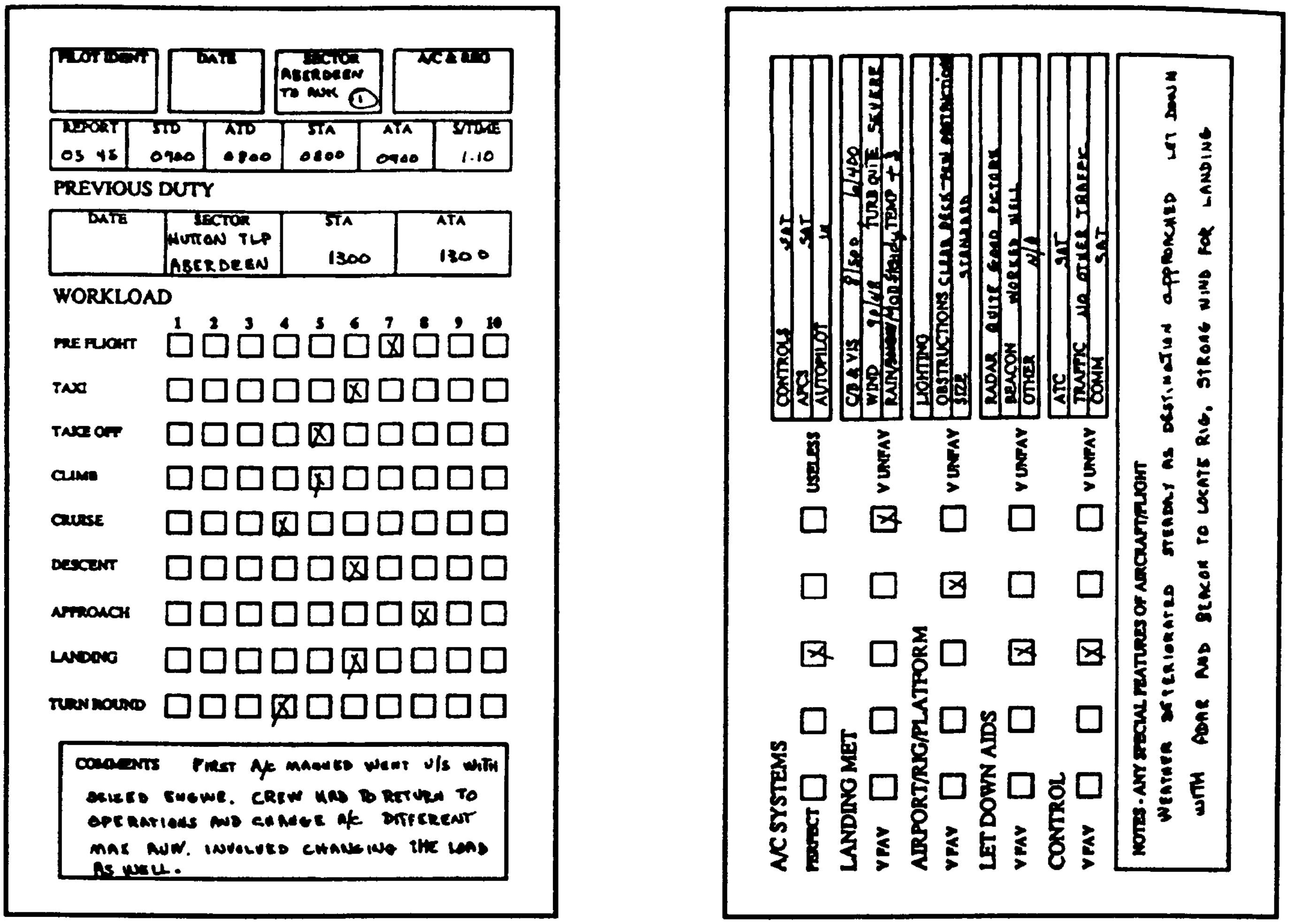
Fatigue ratings were higher posttrip (mean = 48.79) than pretrip (mean = 44.49, $t = -1.93$, $p = 0.05$). Fatigue, negative affect, and activation showed significant time-of-day variation. The significant interactions (time-of-day by pre/trip/post) suggest that the time-of-day variation in fatigue and mood ratings was different across pretrip, trip, and posttrip days. This is illustrated in **Fig. 5**, and is further examined in **Table IV**, which compares the pretrip, trip, and posttrip values in each 4 h time-bin (one-way ANOVAs with subjects treated as a random variable). Where the ANOVAs indicated significant differences, post hoc t-tests were used to compare pretrip, trip, and posttrip ratings for the respective 4-h time bins. All the comparisons discussed were significant at least at $p < 0.05$.

At 0900 hours, fatigue was lower on trip days than either pretrip or posttrip. At 1700 hours, fatigue was higher on trip days than pretrip. At 2100 hours, fatigue was higher on trip days and on posttrip days than it was on pretrip days. At 1700 hours, negative affect was higher on trip days than either pretrip or posttrip. At 2100 hours, negative affect was higher on trip days than

TABLE I. TRIP STATISTICS.

	Mean (SD)	Minimum	Maximum	n
On-duty (GMT)	7.42 (2.02)	4.33	12.50	19 subjects
Off-duty (GMT)	14.62 (2.55)	7.75	22.0	19 subjects
Duty hours/day	7.13 (1.67)	3.00	11.83	19 subjects
Nighttime layover (h)	16.97 (3.08)	10.00	23.00	19 subjects
Flight hours/day	3.40 (1.19)	1.13	5.61	10 trips
# Segments/day	2.90 (1.37)	1.00	7.00	10 trips
Segment duration (h)	1.31 (0.55)	0.03	2.55	10 trips
# Segments/trip	11.60 (3.03)	7.00	17.00	10 trips

Note: There were no time zone crossings.



Side A Side B

Fig. 3. Example of a workload rating card. Side A, modified Bedford Scale. Side B, ratings of environmental factors. One card was completed by each subject for each segment flown.

pretrip. At 0900 hours, activation was higher on trip days than either pretrip or posttrip. At 2100 hours, activation was lower on trip days than pretrip.

Caffeine Consumption, Meals and Snacks

Coffee was available in Aberdeen but not in flight on the majority of aircraft. Pilots could also request coffee on the rigs. The number of cups of caffeinated beverages, and the time of day at which they were consumed, were recorded in the daily logbook. All 22 of the crewmembers included in the sleep analyses consumed caffeine at some time during the study. To test if duty demands had an effect on caffeine consumption, a one-way ANOVA (pretrip/trip/posttrip) was performed, with subjects treated as a random variable **(Table V)**.

Post hoc *t*-tests indicated that caffeine consumption was higher on trip days than either pretrip ($0.001 > p > 0.0001$) or posttrip ($0.05 > p > 0.01$).

Food was available in Aberdeen and on the rigs, but not in flight. The time of eating and the classification of meals (breakfast, lunch, dinner, snack) was recorded in the daily logbook. To test whether duty demands had an effect on the number of meals or snacks eaten per day, one-way ANOVAs were performed, with subjects treated as a random variable (Table V). Post hoc *t*-tests revealed that fewer snacks were eaten per day posttrip than either pretrip ($0.05 > p > 0.01$), or on trips ($0.05 > p > 0.01$).

Physical Symptoms

The logbook also contained a table for each day for noting physical symptoms (9). Of the 22 subjects, 18 included in the analyses (82%) reported symptoms at some time during the study. The three most common symptoms were: headaches (34% of all reports; reported by 73% of subjects at some time during the study); back pain (18% of all reports; reported by 32% of subjects at some time during the study); and burning eyes (10% of all reports; reported by 18% of subjects at some time during the study). The frequency of reports of each of these symptoms on pretrip, trip, and posttrip days is shown in **Table VI**.

Complaints of headache were twice as common on trip days by comparison with pretrip and posttrip, while reports of back pain increased 12-fold on trips and reports of burning eyes increased 4-fold.

TABLE II. COMPARISONS OF SLEEP MEASURES BEFORE, DURING, AND AFTER TRIPS.

	Pretrip	Trip	Posttrip	p(F)
Sleep onset (GMT)	23.63	22.75	23.42	**
Wakeup (GMT)	7.17	5.58	7.27	***
Sleep latency (h)	0.19	0.49	0.58	***
Sleep duration (h)	7.30	6.43	7.39	**
Total sleep/24 h	7.55	6.71	7.49	**
Difficulty falling asleep?	4.17	3.93	4.33	
How deep was your sleep?	3.25	3.42	3.67	*
Difficulty rising?	3.40	3.32	3.57	
How rested do you feel?	2.97	2.93	3.04	
Sleep rating	13.71	13.64	14.61	*
# awakenings	1.16	1.22	1.14	
Mean heart rate (bpm)	60.39	58.20	59.03	
SD heart rate	4.52	4.39	4.92	
Mean activity (counts/min)	2.34	1.32	1.35	
SD activity	5.79	5.38	4.14	
Mean temperature (°C)	36.01	36.08	36.16	
SD temperature	0.14	0.12	0.15	

* $0.05 > p > 0.01$; ** $0.01 > p > 0.001$; *** $p < 0.001$.

Analysis of Workload

As expected, average workload ratings varied in different phases of flight (Table VI).

For about 10% of flights, a reduction in workload during take-off and landing would have been desirable. The ratings (out of 5) for the environmental factors for each segment are summarized in **Table VII**.

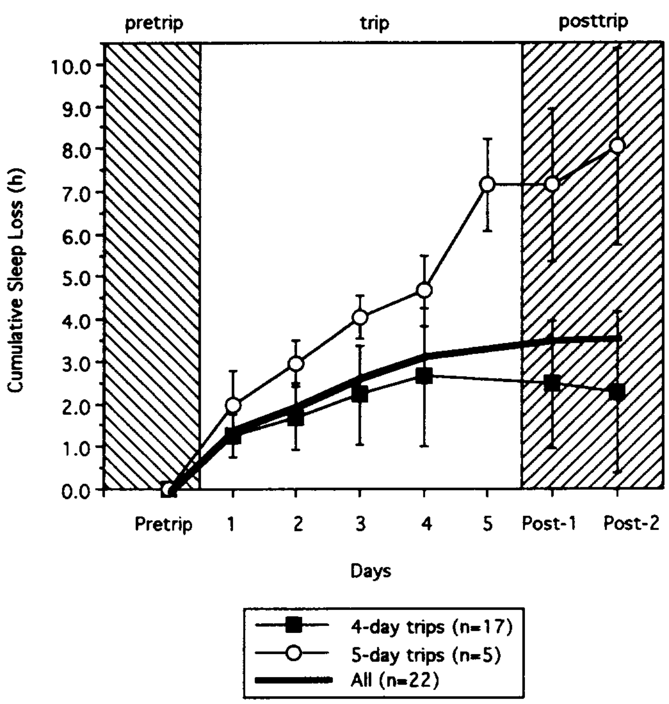


Fig. 4. Average day-by-day cumulative sleep loss with respect to baseline sleep. For each subject, his total sleep per 24 h on each trip day was subtracted from his average total sleep per 24 h on pretrip days, to give a daily measure of sleep loss. Average daily sleep loss was then calculated, and the values added across the consecutive trip days and posttrip days.Vertical lines indicate standard errors. Sleep loss by the end of 5-d trips was not significantly different from sleep loss by the end of 4-d trips.

TABLE III. FATIGUE AND MOOD RATINGS ACROSS PRETRIP, TRIP, AND POSTTRIP DAYS.

	F Ratio Pre/Trip/Post	F Ratio Time-of-Day	F Ratio Interaction
Fatigue	4.16*	26.33***	5.93***
Positive affect	1.11	1.31	1.07
Negative affect	1.42	9.49***	4.79***
Activation	0.45	39.87***	8.97***

* $0.05 > p > 0.01$; *** $p < 0.001$.

Segments were also categorized by their position in the daily flight schedule (first, second, third, etc. segment flown) and by season (winter/spring vs. summer/autumn). For each phase of flight, an analysis of variance was performed to examine the effects of the seven environmental factors (five ratings plus segment number and season) on workload **(Table VIII)**. There were significant differences among subjects for workload ratings during every phase of flight.

The quality of aircraft systems influenced workload ratings from preflight through cruise, with the exception of during takeoff. Weather at the landing site affected workload during preflight, descent, and approach. The quality of the landing site ("airport" in Table VIII) influenced workload during preflight and landing. There were seasonal differences in the workload associated with turnarounds. Since ratings on the five environmental factors were not independent, for each phase of flight smaller ANOVAs were performed which included different subsets of factors. These additional analyses are described in detail elsewhere (7). The ANOVA models with subsets of factors suggested the following relationships, in addition to those identified in the ANOVAs with all seven factors (Table VIII). Segment number had

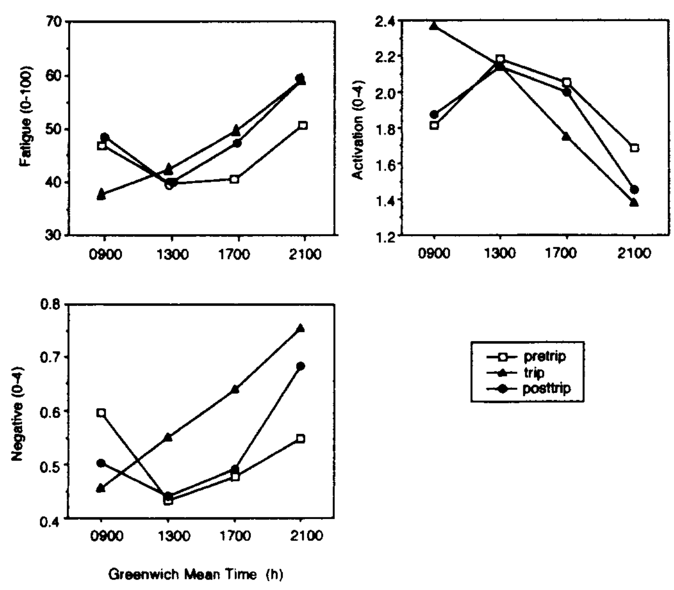


Fig. 5. Average fatigue and mood ratings at different times of day, comparing pretrip, trip, and posttrip days.

TABLE IV. FATIGUE AND MOOD RATINGS AT DIFFERENT TIMES OF DAY COMPARING PRETRIP, TRIP, AND POSTTRIP DAYS.

	F Ratio 0900 Hours Time-Bin	F Ratio 1300 Hours Time-Bin	F Ratio 1700 Hours Time-Bin	F Ratio 2100 Hours Time-Bin
Fatigue	7.43**	0.69	4.03*	13.06***
Negative affect	1.65	2.03	3.68*	4.05*
Activation	10.66***	0.16	2.86	6.05**

* 0.05 > p(F) > 0.01; ** 0.01 > p(F) > 0.001; *** p(F) < 0.001.

a significant effect on preflight workload ratings. Depending on which subset of variables was included, season or segment number had a significant effect on workload ratings during taxi. For workload during landing, there was a significant interaction between the quality of the landing site and the quality of air traffic control.

Comparisons With Short-Haul Fixed-Wing Operations

Table IX compares (by 2-group *t*-tests) demographic and personality measures between the helicopter crewmembers and the short-haul fixed-wing crewmembers described in the second paper of this series (8,10). The fixed-wing statistics are for the subset of 44 subjects included in the sleep analyses in ref. 10.

Including military and other experience increased the average years of experience for the helicopter crewmembers to 10.68, but this was still significantly less than that of the short-haul fixed-wing crewmembers (2-group $t = -3.84$, $0.001 > p > 0.0001$). Helicopter pilots were 9 yr younger, weighed less (perhaps because of the age difference) and scored slightly lower on the expressivity scale of the Personal Attributes Questionnaire.

Table X compares (by 2-group *t*-tests) the duty characteristics of the helicopter operations with those of the short-haul fixed-wing operations (for the trips flown by the 44 subjects included in the sleep analyses in ref. 10)

The helicopter crewmembers began work about an hour earlier, but had duty days more than 3 h shorter, and nighttime layovers more than 4 h longer, than their short-haul fixed-wing counterparts. Their duty days averaged about an hour less flight time and two flight segments fewer. Recall also that the helicopter crews returned home each night, whereas the short-haul crews slept in en route layover hotels during trips.

Table XI compares (by 2-group *t*-tests) changes in sleep from pretrip nights to trip nights, for helicopter and short-haul fixed-wing operations. The later data includes 33 pilots who gave pretrip baseline data. There were no significant differences between the groups on these measures.

Both groups increased their daily caffeine consumption on trips by about 50% over pretrip levels (10). Headaches were the most commonly reported physical symptom in both studies. They were reported by 73% of helicopter pilots at some time during the study, compared with 27% of fixed-wing pilots. Back pain was the second most common symptom reported by helicopter pilots (32%), and was the third most common symptom reported by fixed-wing pilots (11%). The second most common symptom reported by fixed-wing pilots was congested nose (20%). The third most common symptom reported by helicopter pilots was burning eyes (18%).

TABLE V. CONSUMPTION OF CAFFEINE MEALS AND SNACKS BEFORE, DURING, AND AFTER TRIPS.

	Pretrip	Trip	Posttrip	F
Caffeine, servings/day	3.14	4.73	3.46	10.55***
Number of meals/day	2.27	2.58	2.25	2.53
Number of snacks/day	1.20	1.26	0.83	5.71**

*** p < 0.001.

DISCUSSION

Helicopter servicing of the North Sea oil fields is a large and very challenging operation. There are many factors in this environment which can contribute to flight crew fatigue. Some are impossible to modify directly, for example, extreme weather conditions. Others cannot be modified, at least in the short term, because of technological or financial constraints. These include: limited automation of aircraft systems; operating aircraft near the limit of their range and performance capabilities; and difficult landing sites. Given these constraints, it is particularly important to identify those aspects of the operations which can be modified to reduce the likelihood of fatigue impairing flight crew performance.

Crewmembers averaged about 50 min less sleep on trip nights than pretrip, primarily due to the fact that they had to wake up about 1.5 h early to report for duty. Multiple regression analyses reported elsewhere (7) indicated that the time of going on duty the next morning accounted for 41% of the variability in sleep duration. Comparing the total sleep per 24 h (including naps) on trip days vs. pretrip days, 50% of crewmembers averaged more than 1 h of sleep loss on trip days and 14% averaged more than 2 h of sleep loss. In the laboratory, 1 h of sleep loss per night produces a cumulative increase in sleepiness (2). Reducing nighttime sleep in the laboratory by more than 2 h can impair performance and cause

TABLE VI. FREQUENCY OF REPORTS AND COMMON PHYSICAL SYMPTOMS.

Symptom	% Pretrip	% Trip	% Posttrip
Headache	33	52	15
Back pain	7	86	7
Burning eyes	17	66	17

TABLE VII. AVERAGE WORKLOAD RATINGS DURING DIFFERENT PHASES OF FLIGHT.

Phase of Flight	Mean (SD)	% Acceptable (1–3)	% Acceptable For Limited Time (4–6)	% Unacceptable (7–10)*
Preflight	3.56 (1.50)	59	35	5
Taxi	3.62 (1.64)	54	40	7
Takeoff	4.53 (1.58)	29	59	11
Climb	4.02 (1.42)	41	54	5
Cruise	3.38 (1.24)	60	38	2
Descent	3.61 (1.16)	51	47	2
Approach	4.21 (1.35)	32	61	6
Landing	4.60 (1.52)	28	62	10
Turnaround	3.40 (1.51)	59	34	6

* Scores 6–7 indicate that a reduction in workload is desirable, scores 8–10 indicate an increasing potential for overload.

changes in sleep architecture that indicate insufficient sleep (3). On the other hand, 32% of crewmembers reported averaging more sleep on trip nights than pretrip. On trip nights, crewmembers succeeded in falling asleep somewhat earlier (average 48 min) but took longer to fall asleep (average 18 min). This stands in contrast to the shorter sleep latencies observed in the laboratory with increasing sleep debt (3). There are several physiological factors which make it difficult to fall asleep earlier than usual. Sleep onset is less likely at certain phases of the circadian cycle (the so-called "wake maintenance zones"), one of which occurs shortly before the habitual bedtime (15,16). Because the "biological day" dictated by the circadian clock tends to be longer than 24 h, it is easier to go to sleep later than to go to sleep earlier. Going to sleep later also means staying awake longer, which allows more time for the homeostatic "sleep pressure" to build up (1,5).

Crewmembers rated their sleep as better overall on posttrip nights than on trip nights, and deeper on posttrip nights than pretrip. This is consistent with the polygraphically confirmed observation in the laboratory that recovery sleep after sleep restriction is deeper (3).

Fatigue was rated as significantly higher posttrip than pretrip, possibly indicating an accumulated effect of duty demands and sleep loss. In the first rating on trip mornings, fatigue was lower and activation higher than either pretrip or posttrip. This is somewhat surprising given the early wakeup times and shortened sleep on trips. It may reflect increased motivation associated with going on duty. By the end of trip days, fatigue and negative affect were higher, and activation was lower than by the end of pretrip days, suggesting an impact of duty-related activities on these measures. Multiple regression analyses (7) indicated that the later crewmembers stayed on duty, the higher their fatigue ratings by the end of the day. Similarly, the longer they remained on duty, the more negative their mood became. Going on duty earlier resulted in a lower activation rating by the end of the day, possibly because of the associated sleep loss. Fatigue, activation, and negative affect ratings showed significant time-of-day variation, as was found for short-haul fixed-wing crewmembers (10). Neither group showed significant time-of-day variation in positive affect.

Caffeine consumption increased by 42% on trip days by comparison with pretrip and posttrip days. Most of this extra consumption occurred shortly after wakeup (which was earlier on trips) and around the time of the mid-afternoon peak in physiological sleepiness (7). Since caffeine was not usually available in flight, the afternoon increase in caffeine consumption presumably occurred after duty (see Table I). The urge to fall asleep in the afternoon would be expected to increase progressively with the sleep loss accumulating across trip days (2). Headaches affected 73% of subjects at some time during the study, while back pain affected 32% and burning eyes 18%. On trips, the incidence of headaches doubled, back pain increased 12-fold, and burning eyes quadrupled, by comparison with home.

Comparing these operations to the short-haul fixed-wing operations examined in the first NASA fatigue field study (8,10), helicopter crews worked shorter duty days (by an average of 3.4 h) with fewer flight segments (by an average of 2.1) and fewer flight hours (by an average of 0.9 h). They also had longer nighttime layovers (by an average of 4.2 h). A 2-group t-test did not indicate a significant difference between the helicopter and short-haul fixed-wing groups in their sleep loss on trip nights, by comparison with pretrip nights. However, fewer helicopter crewmembers averaged more than 1 h of sleep loss per day on trips (50% vs. 67% of fixed-wing crew-

TABLE VIII. AVERAGE SCORES FOR THE FIVE ENVIRONMENTAL FACTORS.

Environmental Factors	Mean (SD)	% Favorable (1–2)	% Neither (3)	% Unfavorable (4–5)
Aircraft systems	1.79 (0.91)	83	11	6
Landing weather	1.93 (1.00)	74	16	9
Airport	1.94 (0.88)	75	21	4
Letdown aids	1.98 (1.05)	69	24	7
Air traffic control	1.88 (0.87)	77	19	4

TABLE IX. EFFECTS OF ENVIRONMENTAL FACTORS ON WORKLOAD DURING DIFFERENT PHASES OF FLIGHT.

Phase of Flight	F Ratio Season	F Ratio Segment Number	F Ratio Aircraft Systems	F Ratio Landing Weather	F Ratio Airport	F Ratio Letdown Aids	F Ratio Air Traffic Control
Preflight	0.63	1.73	4.75**	4.43**	3.85*	0.86	0.61
Taxi	3.06	3.02*	3.02*	2.03	0.23	1.31	2.00
Takeoff	4.72	1.95	1.43	0.56	0.60	1.25	0.60
Climb	1.44	2.15	4.27**	0.47	0.10	0.57	1.67
Cruise	1.60	1.51	2.79*	1.22	0.93	0.28	0.38
Descent	2.20	0.46	2.48	5.65**	1.93	0.34	0.67
Approach	2.18	1.30	1.21	7.90***	0.56	0.37	0.82
Landing	3.45	0.65	2.57	0.53	6.33**	0.78	0.32
Turnaround	5.88*	0.64	0.68	0.65	0.31	0.28	1.16

* $0.05 > p > 0.01$; ** $0.01 > p > 0.001$; *** $p < 0.001$.

members), and more helicopter crewmembers slept more per 24 h on trips than pretrip (32% vs. 12% of fixed-wing crewmembers). This comparison suggests that sleep loss was less severe during the helicopter operations. However, the estimates of sleep loss for the fixed-wing operations may have been exaggerated by the practice of crewmembers napping strategically on the day before the trip. This inflated their total pretrip baseline sleep, against which sleep loss was calculated (10). It is noteworthy that providing helicopter crews with 4.2 h more layover time did not prevent them from losing sleep. This highlights the importance of the timing of the layover. The helicopter crews finished work much earlier than the fixed-wing crews, but they also had to report for duty earlier (by 1.2 h on average). They were not able to advance their sleep sufficiently to compensate for these early wakeups, i.e., the additional layover time in the afternoon did not serve as additional time for sleep, at least in part because of the physiological constraints on sleep timing outlined above. In contrast to their fixed-wing counterparts, the helicopter crewmembers did not report consistently poorer sleep quality on trip nights compared with pretrip or posttrip. Two factors may have contributed to this. First, the helicopter crewmembers were younger (by an average of 9 yr). Second, they returned home each night, whereas the fixed-wing crews slept in en route layover hotels while on trips.

Helicopter crewmembers showed duty-related changes in fatigue and mood ratings, reporting greater fatigue, lower activation, and more negative mood by the end of trip days than by the end of pretrip or posttrip days. Comparable changes were not reported by the fixed-wing crewmembers, after allowing for the time-of-day variation in these measures (10). Complaints of headache and back pain were three times more common among helicopter crewmembers than among fixed-wing crewmembers. These differences may be related to the more physically stressful working environment of the helicopter cockpits. A study on the thermal environment in these cockpits (11) indicated that core temperatures of pilots remained below the level where any performance decrement due to heat stress might be expected. However, 40–50% (depending on the season) of the skin temperature readings fell outside the range of thermal comfort (33–34.5°C). Poor ventilation and airflow on many flightdecks probably accentuated sensations of physical discomfort (Barnes RM. Unpublished observations). A study on vibration exposures in these cockpits (12) found that all the helicopters exceeded the "reduced comfort" boundary defined by the International Standards Organi-

TABLE X. PILOT CHARACTERISTICS, HELICOPTER VS. SHORT-HAUL FIXED-WING OPERATIONS.

	Mean (SD) Helicopter	Mean (SD) Fixed-Wing	t
Age (yr)	34.32 (6.66)	43.02 (7.65)	4.54***
Experience (yr)	8.64 (4.35)	17.07 (6.56)	6.22***
Height (in)	70.73 (2.66)	70.59 (1.86)	0.24
Weight (lb)	164.80 (4.10)	174.84 (2.15)	2.15*
Personal Attributes Questionnaire			
Instrumentality	21.36 (3.71)	23.27 (3.94)	1.89
Expressivity	19.55 (3.84)	22.34 (4.40)	2.53*
I + E	2.41 (1.10)	2.84 (1.01)	1.59
Work and Family Orientation			
Mastery	21.32 (3.55)	19.95 (4.10)	1.33
Competitiveness	12.27 (3.93)	12.57 (3.49)	0.31
Work	17.68 (2.06)	17.66 (2.09)	0.04
Eysenck Personality Inventory			
Neuroticism	8.15 (4.73)	6.58 (4.51)	1.27
Extraversion	9.52 (3.72)	10.91 (3.46)	1.46
Lie Scale	3.27 (2.00)	3.41 (1.92)	0.27
Morning/Eveningness	59.82 (8.27)	63.41 (9.47)	1.51

* $0.05 > p > 0.01$; *** $p < 0.001$.

TABLE XI. DUTY CHARACTERISTICS, HELICOPTER VS. SHORT-HAUL FIXED-WING OPERATIONS.

	Mean (SD) Helicopter	Mean (SD) Fixed-Wing	*t*
On-duty (local time)	7.47 (2.20)	8.71 (3.14)	3.62***
Off-duty (local time)	14.77 (2.53)	19.06 (3.54)	11.05***
Duty hours/day	7.30 (2.53)	10.66 (2.41)	12.81***
Nighttime layover duration (h)	16.77 (3.05)	12.52 (2.52)	10.14***
Flight hours/day	3.58 (1.11)	4.50 (1.39)	5.08***
Flight segments/day	3.02 (1.46)	5.12 (1.34)	8.82***
Flight hours/month	61.48 (18.69)	70.21 (9.92)	1.95

*** $p < 0.001$.

zation (ISO 263), and several approached or exceeded the "fatigue decreased proficiency" boundary. This is the limit beyond which exposure to vibration can be regarded as carrying a significant risk of impaired working efficiency. Improved seat design, and improved isolation of the seat from floor vibration were recommended as countermeasures. The 12-fold increase in reports of back pain during trips reinforces the importance of this recommendation.

The workload ratings in this study tended to be higher than those during the flight test evaluation of workload in a shorthaul fixed-wing aircraft (Barnes RM. Unpublished observations). Preflight workload ratings were influenced by segment number, landing weather, the landing site, and the quality of the aircraft systems. This is consistent with the fact that the aircraft were often operating near the upper limit of their range and in poor weather, with limited alternate landing sites. Paperwork was also cited by pilots as an important source of workload during preflight. Efforts to reduce and standardize paperwork have since been undertaken (13). Workload ratings during taxi were affected by the quality of aircraft systems, the flight segment number, and the season, depending on which variables were included in the ANOVA model. Pilots also cited weather and traffic conditions at peak times as important contributing factors to their perceived workload during taxi.

None of the environmental factors tested had a significant effect on workload ratings during takeoff. During climb and cruise, the only significant factor found was the quality of the aircraft systems. However, the cockpit observers noted that the high workload associated with climb can be exacerbated by heavy ATC demands in the presence of other traffic. Although the present analyses did not identify landing weather as factor affecting workload during cruise, the cockpit observers noted that, in poor weather, the non-flying pilot could spend a considerable amount of time obtaining weather information from various rigs.

TABLE XII. CHANGES IN SLEEP FROM PRETRIP TO TRIP NIGHTS: COMPARING HELICOPTER AND SHORT-HAUL FIXED WING CREWS.

	Helicopter	Short-Haul Fixed-Wing	*t*
Sleep onset time (h)	−0.88	−0.31	1.32
Sleep latency (min)	18.22	25.55	1.35
Wakeup time (h)	−1.59	−1.53	0.16
Sleep duration (h)	−0.87	−1.37	−1.53

During descent and approach, the landing weather had a major effect on the subjective workload ratings. This is consistent with the fact that weather conditions in the North Sea oil fields often present a hostile environment for helicopter operations, including high winds, reduced visibility due to fog banks and low cloud, icing, turbulence over the rigs, and, at low levels, salt spray. Subjective ratings of workload during landing were associated with the quality of the landing site and the air traffic control. Traffic control, at sites other than airfields, is usually procedural in the terminal areas, requiring a high level of alertness. Turbulence over the rig, obstructions, and the size of the landing area may also increase workload. Landings on platforms on tankers at fixed moorings often require fine judgment because of the additional problems of heave and sway.

A number of recommendations about ways to reduce fatigue can be made on the basis of these findings. First, the scheduling practice of requiring early duty report times effectively reduces the time available for sleep, even during long layovers. This is because physiological factors tend to oppose falling asleep earlier than the usual bedtime. Delaying on-duty times (by 1.5–2.0 h on average) would be expected to produce a significant improvement in the amount of sleep that crewmembers are able to obtain.

Second, the challenging physical environment of the helicopter flightdeck, combined with high workload, might be expected to contribute to the high incidence of headaches and back pain reported, and to the increase in subjective fatigue and negative mood across duty days. Improvements in seat design, in the isolation of the seat from floor vibration (12), and in ventilation on the flightdeck, could be beneficial.

Third, the quality of aircraft systems was perceived by crewmembers to have an important effect on workload during preflight, taxi, climb, and cruise. This suggests that workload reduction during these phases might be achieved by improving aircraft maintenance. The data also support the idea that the impact of adverse weather on subjective workload during descent and approach can be reduced by improving the quality of the letdown aids and the landing site.

ACKNOWLEDGMENTS

This work was made possible by the enthusiasm and dedication of the pilot volunteers and the generous cooperation of the following companies: British Airways Helicopters Ltd. (now British International Helicopters Ltd.); British Caledonian Helicopters Limited; Bristows Helicopters Ltd.; and Bond Helicopters Ltd. We gratefully acknowledge the invaluable assistance of Hazel Courtney and Keith Biggin of Westland Helicopters, who served as cockpit observers, and the Statistics Department of the RAF Institute of Aviation Medicine at Farnborough, where the workload data were analyzed.

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Flight Crew Fatigue IV: Overnight Cargo Operations

PHILIPPA H. GANDER, PH.D., KEVIN B. GREGORY, B.S., LINDA J. CONNELL, M.A., R. CURTIS GRAEBER, PH.D., DONNA L. MILLER, B.A., AND MARK R. ROSEKIND, PH.D.

GANDER PH, GREGORY KB, CONNELL LJ, GRAEBER RC, MILLER DL, ROSEKIND MR. *Flight crew fatigue IV: overnight cargo operations.* Aviat Space Environ Med Aviat Space Environ Med 1998; 69(9,Suppl.): B26–36.

We monitored 34 B-727 crewmembers before, during, and after 8-d commercial overnight cargo trips crossing no more than one time zone per 24 h. Daytime sleep episodes were 41% shorter and were rated as poorer than nighttime sleep episodes. When the layover was long enough, crewmembers usually slept again in the evening before going back on night duty. Nevertheless, the total sleep per 24 h on duty days averaged 1.2 h less than pretrip. The circadian temperature rhythm did not adapt completely to night duty, delaying by about 3 h. Self-rated fatigue was highest around the time of the temperature minimum, which occurred near the end of the nighttime duty period. On trip days, crewmembers ate more snacks and there was a marked increase in reports of headaches, congested noses, and burning eyes. Comparisons with daytime short-haul operations confirm that a daytime rest period does not represent the same sleep opportunity as a nighttime rest period of the same duration. We examine regulatory and scheduling options, and personal countermeasure strategies, that could help to reduce sleep loss during overnight cargo operations.

IN 1987–88, the fatigue Countermeasures Program at NASA-Ames conducted a field study to assess fatigue in domestic overnight cargo operations. This study offered an opportunity to compare the affects of night vs. day flying because the same measures of fatigue were collected as in the daytime short-haul operations examined in the first NASA fatigue field study (14,15). Both types of operations included multiple flight segments per duty day and minimal time zone crossings.

In other industries, shift workers are three times as likely to complain of sleep problems as day workers, with night work being experienced as the most disruptive (1,6,37). It has been estimated that 75% of all workers experience sleepiness on every night shift, and that for at least 20% it is severe enough to cause them to fall asleep (1). A NASA-FAA study of preplanned cockpit rest in three-person long-haul flight crews (32) has compared the sleepiness and performance of crews on daytime and nighttime flights. During eastward nighttime trans-Pacific flights, sleep propensity was higher and performance was poorer (on a sustained attention, vigilance-reaction time test) than during westward daytime trans-Pacific flights. The additional challenges of night work, and their potential affects on efficiency and safety, have been highlighted in several recent publications (1,22,23,37).

Working at night creates conflict among environmental time cues to the circadian clock. It is partially reset by the altered work/rest schedule, but is continually being drawn back toward a diurnal orientation by the day/night cycle and the daytime orientation of the rest of society (1,24,37). The clock may continue to adapt progressively across a series of night duties (24). However, any adaptation is usually lost on days off, when most people revert to sleeping at night. Incomplete circadian adaptation to night work has two important consequences for fatigue and on-the-job performance. First, night workers may be working at times in the circadian cycle when their subjective fatigue and physiological sleepiness are greatest, and when they are most vulnerable to performance errors (1,7,26). Second, their daytime sleep is often compromised because they are trying to sleep when they are physiologically prepared for wakefulness, and when disturbances (noise, light, domestic or other social demands) are maximal.

Frequent changes in the sleep/wake pattern can result in chronic desynchronization of the circadian clock from the environment, and chronic desynchronization between different physiological rhythms (35). This may be a contributing factor to the long-term effects of shift work on health, including increased incidence of gastrointestinal and cardiovascular illness among shift workers (37). The quality of food available and the irregular eating habits of many shift workers probably also contribute to their increased risk of gastrointestinal problems.

Individual differences in adaptation to shift work in other industries have been reported to be correlated with several circadian characteristics and personality profiles. Better tolerance has been associated with higher amplitude circadian rhythms (30,35), and a more "evening-type"profile (2,9,19,20,21,24,27). In a group of commercial long-haul flight crewmembers, Sasaki et al. (34) found that evening-types showed lower levels of day-

Fatigue Countermeasures Program, NASA-Ames Research Center, Moffett Field, CA; San Jose State University Foundation (P. H. Gander); Sterling Software, Inc.(K. B. Gregory, D. L. Miller); NASA-Ames Research Center (L. J. Connell, M. R. Rosekind); and Boeing Commercial Airplane Group (R. C. Graeber).

Address reprint requests to: Philippa H. Gander, Ph.D., who is currently a professorial research fellow in the Department of Public Health, Otago University at Wellington School of Medicine, P.O. Box 7343, Wellington South, New Zealand.

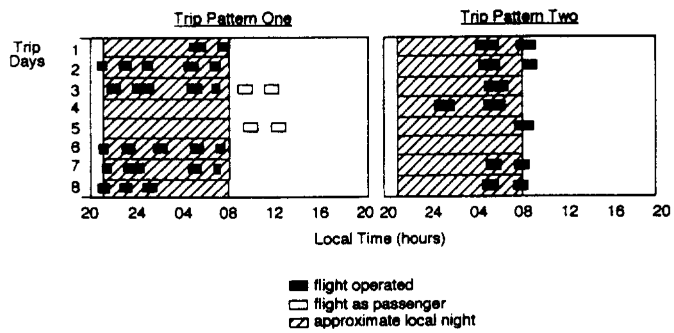

Fig. 1. The two 8-d trip patterns studied.

time sleepiness after operating an eastward flight crossing eight time zones than did morning-types. It has also been reported that individuals who score high on the extroversion and neuroticism scales of the Eysenck Personality Inventory (8) may adapt more rapidly than other personality types to schedule changes (7). In a study of Norwegian Air Force pilots, more extraverted individuals showed greater adaptation of the circadian temperature rhythm 5 d after a westward flight crossing nine time zones (16,17). These relationships account for only a very small amount of the observed individual variability and do not yet permit prediction of who is most likely to experience performance decrements as a result of fatigue.

METHODS

Two 8-d trip patterns were selected for study from the monthly bid packages of the participating airline. They were chosen, after discussion with flight crewmembers and flight operations personnel, as being representative of the two most challenging patterns that were common in the industry at that time.

All flights took place in the central and eastern U.S., crossing no more than one time zone in 24 h. Data were collected from November 1987 through December 1988. Half of the trips took place during Daylight Time, and half during Standard Time. All data were collected on Greenwich Mean Time (GMT) and converted to local time where appropriate in the analyses.

On Trip Pattern 1 (**Fig. 1**), crews usually slept away from home between consecutive nights of flying. After 3 nights of flying, they deadheaded home (flew as passengers, but were on duty) and had about 45 h off duty before deadheading from their domicile to begin another 3 nights of flying. On Trip Pattern 2 (Fig. 1), crews usually slept at home between consecutive nights of flying. After 5 nights of flying, they arrived home and had about 45 h off duty before beginning another 2 nights of flying. Because of the 45-h break from duty, the 8 trip days were separated into duty and no-duty days in the analyses.

Two-group *t*-tests indicated that the two trip patterns differed significantly in the following: the average on-duty time; daily duty duration; layover duration; number of flight segments per night; average segment duration; number of flight hours per night; number of segments per trip; and number of hub turns per trip. The two trip patterns were comparable for the following: average off-duty time; and duration of the no-duty day (14). We were initially surprised to find that there were no significant differences between the two trip patterns in the amount of sleep per 24 h obtained by crewmembers during any stage of the study (pretrip, duty days, the no-duty day, or posttrip). Further investigation indicated that this was due to the marked day-by-day variability in duty parameters within each trip pattern. It was therefore decided to combine the data from both trips, and relate the observed changes to the day-by-day duty characteristics, rather than making global comparisons between the two trip patterns.

There were 41 Boeing-727 crewmembers (two-person crews) who volunteered to participate (39 male, 2 female). To be included in the analyses, crewmembers had to have provided logbook data for at least one pretrip night, all trip nights, and two posttrip nights. There were 20 crewmembers (87%) on Trip Pattern 1 and 14 crewmembers (78%) on Trip Pattern 2 who met this criterion. Their average age was 37.6 yr (SD 4.76 yr) and they had been with their present airline an average of 4.7 yr (SD 4.17 yr). This represents a minimum estimate of how long they had been flying overnight cargo operations. No significant differences were found (2-group *t*-tests) on a variety of demographic and personality measures between crewmembers flying the two trip patterns (14).

Unless otherwise stated, all analyses of variance (ANOVA) were within subjects. For *t*-tests, where a Levene's test revealed unequal variances, the separate *t*-test value was taken. Otherwise, the pooled *t*-test value was taken.

In addition to the logbook measures of fatigue, in this study particular attention was focused on the adaptation of the circadian clock to duty demands. Following current convention, the core temperature rhythm (measured at 2-min intervals) was used to monitor the position of the circadian clock. However, changes in the level of physical activity cause changes in temperature which are superimposed on the circadian variation. Estimating circadian phase in the presence of these masking affects is complex, particularly when people are not sleeping at the same time on consecutive days, as in the present data. To compensate for the masking of the circadian temperature rhythm by the sleep-wake cycle, a constant (0.28°C) was added to the raw temperature data for each crewmember whenever he or she was asleep. This mathematical "unmasking" procedure was based on the reported 0.28°C difference between the temperature rhythm during sleep and wake in internally desynchronized people in a time-free environment (38). Masked and unmasked temperature data for each crewmember were averaged in 20-min bins and subjected to multiple complex demodulation (29) to estimate the amplitude of the pretrip baseline temperature rhythm and the cycle-by-cycle temperature minima. The cycle-by-cycle temperature minimum was taken as the computer-selected lowest value within 12 h in the remodulated waveform. If this procedure identified two minima in 24 h, then the data and the remodulated waveform were superimposed on the sleep and nap times. If there was no clear way of discriminating between the minima (circadian or mask-

TABLE I. COMPARISONS OF SLEEP MEASURES BEFORE, DURING, AND AFTER TRIPS.

	Pretrip	Duty	No-Duty	Post	F
Sleep onset (local time)	0.55	5.72	0.69	0.56	92.90***
Wakeup (local time)	8.21	10.29	8.83	7.94	15.74***
Sleep latency (min)	14.11	17.81	25.04	21.89	1.99
Sleep duration (h)	7.46	4.56	8.09	7.21	40.90***
Total sleep/24 h	7.54	6.31	8.23	7.65	10.62***
Difficulty falling asleep?	4.21	4.12	4.23	4.04	0.35
How deep was your sleep?	3.65	3.39	4.06	3.76	5.54**
Difficulty rising?	3.48	3.31	3.38	3.69	1.60
How rested do you feel?	3.27	2.66	3.28	3.40	5.40**
Sleep rating	14.60	13.43	14.97	14.88	3.84*
# Awakenings	1.68	0.81	1.15	1.13	10.98**
Mean heart rate (bpm)	62.78	63.23	60.98	61.56	1.81
SD heart rate	6.89	6.55	6.41	6.88	0.56
Mean activity (counts/min)	2.77	2.62	1.31	1.70	1.19
SD activity	7.06	6.11	5.18	6.31	0.81
Mean temperature (°C)	36.74	36.81	36.66	36.72	3.92*
SD temperature	0.12	0.11	0.14	0.14	1.75

* $0.05 > p > 0.01$; ** $0.01 > p > 0.001$; *** $p < 0.001$.
Note: The average times of sleep onset and wakeup on trip days are somewhat misleading because of the occurrence of split sleeps.

ing), then the data for that cycle were discarded. Missing points in the raw data were replaced by linear interpolation, and all the fitted waveforms were overlaid with the original data to check that the interpolation did not introduce spurious estimates of minima. A detailed description of the affects of the unmasking procedure on the estimation of circadian parameters is contained in reference 14.

RESULTS

Sleep

Table I compares the characteristics of individual sleep episodes on pretrip, duty, no-duty, and posttrip days (one-way ANOVA with subjects treated as a random variable). Where significant differences were found, these were further examined by post hoc *t*-tests. All the comparisons discussed here were significant at least at the 0.05 level.

Sleep latency was calculated as the difference between the reported times of going to bed and falling asleep. Scores on the four sleep quality questions (rated from 1-least to 5-most) were converted so that higher values indicated better sleep, and combined to give the overall sleep rating. Heart rate, temperature, and activity data during each sleep episode were trimmed to include values from 20 min after the reported sleep onset time until 10 min before the reported wakeup time (13). Heart rate and activity data during sleep were available for 24 crewmembers (75%), and the corresponding temperature data were available for 21 crewmembers (65%).

Sleep episodes on duty days occurred later in the day, were shorter, and were rated as less restful and of lower overall quality, than sleep episodes pretrip, on the no-duty day, or postrip. They were also rated as less deep than sleep episodes on the no-duty day or posttrip. The number of reported awakenings varied significantly across pretrip, duty, no-duty, and posttrip sleep episodes. However this difference disappeared if the number of awakenings per hour of sleep was considered. The average temperature during sleep was higher for duty sleep episodes than for no-duty sleep episodes.

In the daily logbooks, it was possible to record up to two sleep episodes and two naps per 24 h. The total sleep per 24 h on duty days was less than on pretrip days, the no-duty day, or posttrip days. Since the total sleep on duty days was 1.2 h less than pretrip, crewmembers accumulated a sleep debt across trip days **(Fig. 2)**. The no-duty day permitted some recuperation, with crewmembers sleeping 41 min more per 24 h than on pretrip days, and 1.9 h more per 24 h than on duty days. The two trip patterns did not differ significantly in the amount of sleep per 24 h during any stage of the study (14). Some 54%of crewmembers averaged more than 1 h of sleep

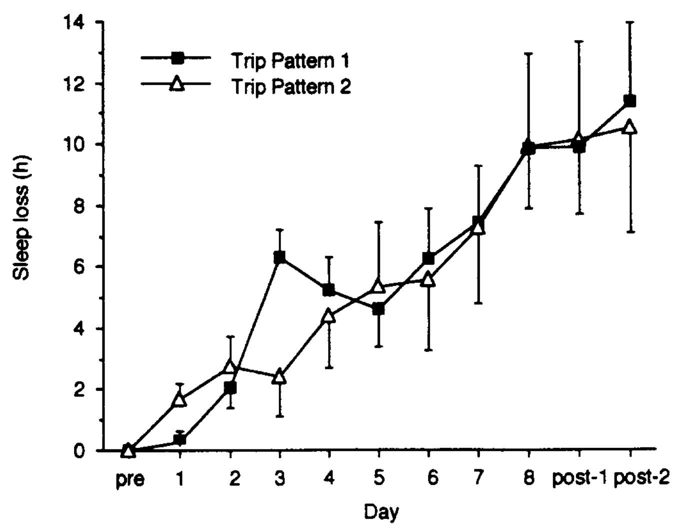

Fig. 2. Average daily sleep loss (h) across the two trip patterns. For each subject, his total sleep per 24 h on each trip day was subtracted from his average total sleep per 24 h on pretrip days, to give a daily measure of sleep loss. Average daily sleep loss was then calculated, and the values added across the consecutive trip days and posttrip days. Vertical bars indicate standard errors.

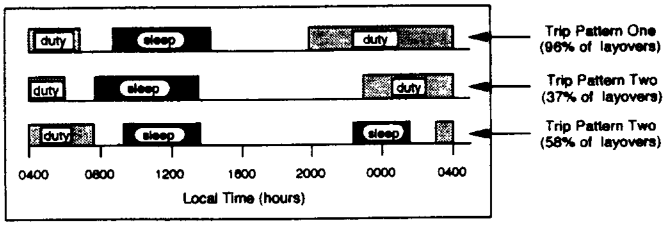

Fig. 3. Average layover and sleep timing for the most common sleep patterns during daytime layovers. On Trip Pattern 1, 96% of layovers included only one sleep episode in the morning. The remaining layovers on this trip pattern included split sleeps. On Trip Pattern 2, 37% of layovers included only one sleep episode in the morning, 58% of layovers included split sleep, and 5% of layovers included one sleep episode in the evening.

loss per 24 h across the 8-d trip patterns, and 29% averaged more than 2 h of sleep loss per 24 h. On the other hand, 15% of crewmembers reported averaging more sleep per 24 h on trip days than on pretrip days. The increasingly large standard errors across trip days in Fig. 2 indicate the increasing divergence among crewmembers in their cumulative sleep debt.

Sleep Patterns and Layover Timing

On duty days, 53% of crewmembers slept more than once in 24 h, compared with 17% on days without duty (i.e., combining pretrip, no-duty, and posttrip days). The incidence of multiple sleep episodes or naps on duty days varied markedly from day-to-day on each trip pattern, and between the two trip patterns (14). This prompted further investigation of the relationship between sleep patterns and layover timing. Naps accounted for very little of the total sleep per 24 h (3% on days with duty, 1.4% on days without duty), and were therefore not included in these analyses. The following analyses include 81 daytime layovers on Trip Pattern 1, and 78 daytime layovers on Trip Pattern 2.

Three basic sleep patterns were observed on daytime layovers: a) crewmembers slept only once in the morning; b) they slept in the morning and again in the evening (split sleep); or c) they slept only once in the evening. This third pattern was observed in only four layovers (5%) on Trip Pattern 2. The two more common sleep patterns are shown in **Fig. 3**. To test whether these different types of sleep episodes (morning or evening, single or split sleep, Trip Pattern 1 or Trip Pattern 2) were statistically distinct, one-way ANOVAs were performed **(Table II)**.

Posthoc Tukey tests with Bonferroni correction were used to compare each type of sleep episode with every other type. Single morning sleep episodes on both duty patterns were indistinguishable in duration and timing. They were longer than either the morning or the evening sleep episodes of split sleep patterns. Single morning sleep episodes also began earlier than first sleep episodes of a pair on Trip Pattern 2. When crewmembers went to sleep in the morning (for a single sleep or the first of two), they tended to wake up at around the same time (combined average 1413 hours local time), irrespective of how long they had been asleep. Wakeup times were indistinguishable for all types of morning sleep episodes (single or first of two; Trip Pattern 1 or Trip Pattern 2).

To test whether sleep patterns were affected by the timing and duration of the layover, one-way ANOVAs were performed comparing layovers with split sleep to layovers with one morning or one evening sleep episode **(Table III)**.

Posthoc Tukey tests with Bonferroni correction were used to compare the different types of layovers. Layovers containing one morning sleep episode began earlier, finished earlier, and were shorter than layovers containing split sleep. Layovers with one morning sleep episode on Trip Pattern 1 were the shortest of the identified layover categories. These analyses indicate that the decision to sleep once or twice in a layover is related to the timing and duration of the layover.

Sleep Loss and Individual Attributes

The average daily percentage sleep loss on duty days (compared for each subject to his own pretrip baseline) has been used previously as a measure of the adaptation of flight crewmembers to duty demands in a number of different types of operations (18). Correlation analyses were performed **(Table IV)** to see if this measure was related to any of the individual attributes previously reported to predict adaptation to shift work in other industries (data from 25 crewmembers). None of these relationships was significant at the 0.05 level.

Circadian Adaptation

There was no clear progressive adaptation (14) of the temperature rhythm to consecutive nights of flying (maximum of 5 consecutive nights on Trip Pattern 2). To test whether the temperature rhythm shifted in response to nighttime flying, a two-way ANOVA was performed for the masked and unmasked temperature minima comparing the two trip patterns on pretrip, duty, no-duty, and posttrip days **(Table V)**. These analyses include data for 12 crewmembers (52%) on Trip Pattern 1, and 6 crewmembers (33%) on Trip Pattern 2.

TABLE II. COMPARISON OF DIFFERENT TYPES OF SLEEP EPISODES ON THE TWO TRIP PATTERNS.

	Trip 1 AM Single	Trip 2 1st of 2	Trip 2 2nd of 2	Trip 2 AM Single	Trip 2 PM Single	F Ratio
Asleep (local h)	9.19	9.73	22.82	8.10	21.77	333.53***
Awake (local h)	14.71	13.94	2.08	14.01	1.71	585.14***
Sleep length (h)	5.44	4.30	3.29	5.79	4.02	19.05***

*** $p < 0.001$.

TABLE III. COMPARISON OF LAYOVERS CONTAINING ONE VS. TWO SLEEP EPISODES.

	Trip 1 AM Single	Trip 2 Two Sleeps	Trip 2 AM Single	Trip 2 PM Single	F Ratio
Off-duty (local h)	7.42	7.99	6.47	8.26	17.17***
On-duty (local h)	20.28	3.47	23.25	3.14	417.57***
Layover length (h)	12.86	19.48	16.68	18.88	241.95***

*** $p < 0.001$.

The two trip patterns did not have significantly different affects on the timing of the daily temperature minimum (14). For both masked and unmasked estimates, post-hoc *t*-tests indicated that the temperature minimum occurred later on duty days than at any other time. For both types of estimates, the timing of the temperature minimum was not significantly different on pretrip, no-duty, or posttrip days. The average times of the daily temperature minima across the study are summarized in **Table VI**.

In general, when crewmembers slept at night, the estimated time of the temperature minimum was earlier for the masked data. In contrast, when they slept during the day, the unmasked data gave the earlier estimate (14). Consequently, the masked estimates in Table VI indicate a larger delay in the temperature rhythm on duty days by comparison with pretrip (3.5 h), than the unmasked estimates (2.8 h). However, these two estimates of the circadian shift were not significantly different (paired *t*-test; $t = -0.62$, $p = 0.54$). Because the temperature rhythm did not adapt completely to night duty, the daily temperature minimum was occurring around the time that crewmembers came off duty **(Fig. 4)**.

Subjective Fatigue and Mood Ratings

Every 2 h while they were awake, crewmembers rated their fatigue level on a 10 cm line from "most alert" to "most drowsy." They also rated their current mood from 0 (not at all) to 4 (extremely) on 26 adjectives which have been shown to load on three orthogonal factors, designated positive affect, negative affect and activation (12). When they were on duty, crewmembers gave ratings at times when they would normally have been asleep. Thus, the affects of duty and of sampling a different part of the (partially shifted) circadian cycle are confounded. In addition, few crewmembers provided complete data and it was necessary to collapse the ratings into 4 h time-bins. Only 4 crewmembers provided fatigue and mood ratings in every 4-h time bin on pretrip, duty, no-duty, and posttrip days. Thus comparisons of time-of-day variation across different stages of the study are comparing different groups of subjects (**Table VII** and **Fig. 5**). Only crewmembers who provided data for every 4-h time bin in a given stage were included.

For ratings made on pretrip days, one-way ANOVAs showed significant time-of-of day variation in fatigue and in activation, but not in positive or negative affect. The time-of-day variations in fatigue and activation were mirror images of each another (Fig. 5), and were similar those reported for short-haul fixed-wing and helicopter pilots on pretrip days (10–12,15).

For ratings made on duty days, fatigue was highest and activation lowest in the 4-h time bin just after the temperature minimum (0830–1230 hours local time). Because of the reduction of the data into 4 h time bins, it was impossible to establish with precision the amount of shift in the fatigue and activation rhythms from pretrip to duty days. On duty days and posttrip days, positive and negative affect also showed significant time-of-day variation. Crewmembers rated their mood as most positive at the same time that they rated their fatigue as lowest.

Fatigue and mood ratings made while on duty at night (0130–0730 hours local time) were compared with those made during the day pretrip (0930–1730 hours local time). One-way ANOVAs, with subjects treated as a random variable, showed that when crewmembers were on duty at night, they rated their fatigue and negative affect as higher, and their positive affect and activation as lower, than during pretrip days **(Table VIII)**.

Caffeine Consumption

Crewmembers could obtain a thermos of coffee from operations and they were provided with a cooler of drinks (water, juice, soda, etc.) in flight (there were no cabin crew). Coffee and snack foods were available at most en route airports and full cafeteria service was available at the hub. Some crewmembers, particularly on Trip Pattern 2, brought their own food and beverages on duty with them. The number of cups of caffeinated beverages, and the time-of-day when they were con-

TABLE IV. INDIVIDUAL DIFFERENCES IN MEAN DAILY PERCENTAGE SLEEP LOSS.

	r^2
Temperature amplitude (masked)	−0.00
Temperature amplitude (unmasked)	−0.16
Neuroticism	−0.04
Extraversion	0.08
Morning/eveningness	0.27

TABLE V. EFFECTS OF NIGHT DUTY ON CIRCADIAN PHASE.

	F Pre/Duty/No-duty/Post	P Trip Patterns	F Interaction
Masked	30.34***	1.03	0.49
Unmasked	11.29***	1.36	0.36

*** $p < 0.001$.

TABLE VI. MEAN LOCAL TIMES (IN HOURS) OF THE DAILY TEMPERATURE MINIMUM.

	Pretrip	Duty	No-Duty	Post
Masked	5.06	8.56	5.67	5.44
Unmasked	5.33	8.13	6.13	6.05

sumed, were recorded in the daily logbook. All of the 34 crewmembers included in the sleep analyses consumed caffeine at some time during the study. To test whether duty demands affected caffeine consumption, a one-way ANOVA (pretrip/duty/no-duty/posttrip) was performed, with subjects treated as a random variable (**Table IX**). Caffeine consumption did not change significantly on duty days.

Meals and Snacks

The time of eating and the classification of meals (breakfast, lunch, dinner) and snacks were recorded in the daily logbook. To test whether duty demands had an effect on the number of meals or snacks eaten per day, one-way ANOVAs (pretrip/duty/no-duty/posttrip) were performed, with subjects treated as a random variable (Table IX). All the post hoc *t*-test comparisons reported here were significant at least at $p < 0.05$. Crewmembers reported fewer meals per day posttrip than either pretrip, or on duty days, or on the no-duty day. More snacks per day were reported on duty days than either pretrip, or on the no-duty day, or posttrip. The low consumption of caffeine, meals, and snacks reported posttrip probably reflects incomplete reporting posttrip.

Physical Symptoms

The logbook also contained a table for each day for noting physical symptoms (13). Of the 34 crewmembers included in the sleep analyses, 28 (82%) reported symptoms at some time during the study. The three most common symptoms were: headaches (42% of all reports, reported by 59% of crewmembers at some time during the study), congested nose (19% of all reports, reported by 26% of crewmembers at some time during the study), and burning eyes (9% of all reports, reported by 18% of crewmembers at some time during the study). The percentage of these reports which occurred on pretrip,

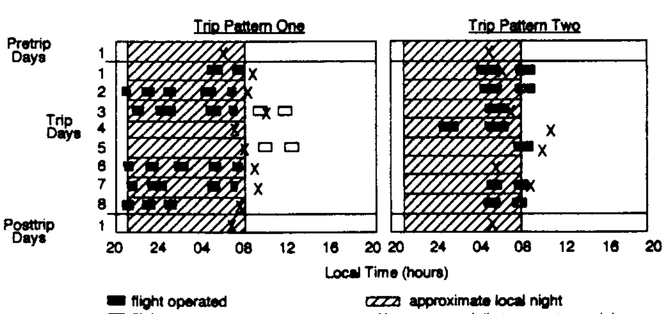

Fig. 4. Average times of the daily temperature minima (x) and flight times on the two trip patterns.

TABLE VII. TIME-OF-DAY VARIATIONS IN FATIGUE AND MOOD RATINGS ACROSS PRETRIP, DUTY, NO-DUTY, AND POSTTRIP DAYS.

	Pretrip F (n)	Duty F (n)	No-Duty F (n)	Posttrip F (n)
Fatigue	7.57 (11)***	13.01 (36)***	2.05 (6)	6.97 (8)***
Positive affect	1.54 (12)	11.46 (37)***	1.22 (8)	3.15 (8)*
Negative affect	1.62 (12)	19.57 (37)***	3.25 (8)*	5.36 (8)**
Activation	7.90 (12)***	12.28 (37)***	2.26 (8)	4.80 (8)**

* 0.05 > p > 0.01; ** 0.01 > p > 0.001; *** p < 0.001.

duty, no-duty, and posttrip days is shown in **Table X**. The incidence of headaches quadrupled on duty days, by comparison with pretrip, while the incidence of congested nose doubled, and of burning eyes increased ninefold.

Comparisons with Daytime Short-Haul Fixed-Wing Operations

Table XI compares (by two-group *t*-tests) the duty characteristics of these overnight cargo operations with those of the daytime short-haul operations described in the second paper of this series (for the trips flown by the 44 subjects included in the short-haul sleep analyses; ref 15).

As expected, the timing of the duty periods was inverted between the two types of operations. Overnight cargo crewmembers spent less time on duty each day (by an average of 3.5 h) and had longer layovers (by an average of 2.4 h) than their daytime short-haul counter-

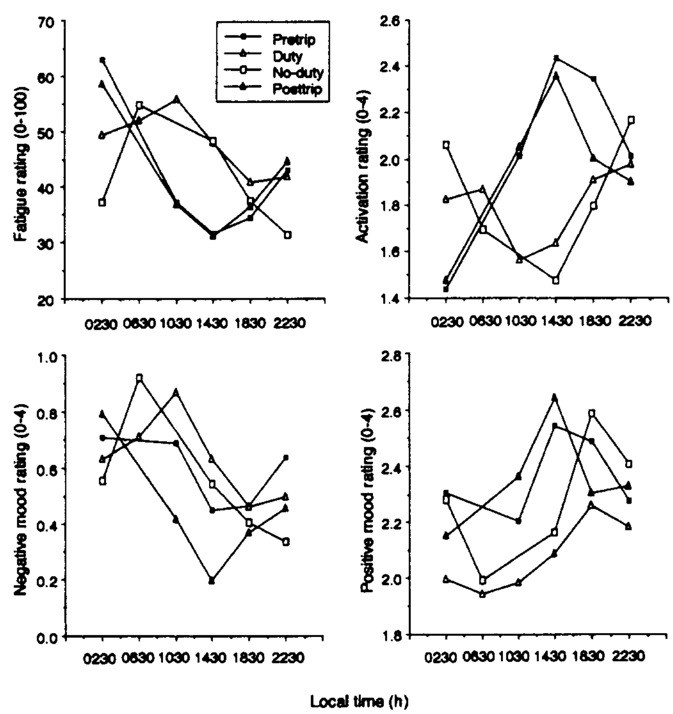

Fig. 5. Average fatigue and mood ratings at different times of day on pretrip, duty, no-duty and posttrip days. The times represent the midpoints of the 4 h data bins.

TABLE VIII. FATIGUE AND MOOD DURING DAYTIME VS. NIGHTTIME WAKE.

	Pretrip Mean	Duty Mean	F
Fatigue	33.46	51.05	53.28***
Positive affect	2.35	1.98	30.65***
Negative affect	0.49	0.68	13.26***
Activation	2.34	1.85	49.13***

*** $p < 0.001$.

TABLE X. FREQUENCY OF REPORTS OF COMMON PHYSICAL SYMPTOMS ON PRETRIP, DUTY, NO-DUTY, AND POSTTRIP DAYS.

Symptom	% Pretrip	% Duty	% No-Duty	% Posttrip
Headache	16.7	72.2	1.9	9.3
Congested nose	16.0	32.0	8.0	44.0
Burning eyes	8.3	75.0	16.7	0.0

parts. Overnight cargo duty days included fewer flight hours (by an average of 2.0) and fewer flight segments (by an average of 2.3).

Table XII compares (by two-group *t*-tests) demographic and personality measures for the two groups of crewmembers. The years of experience was taken as the largest value from among the following categories: years with the present airline; years of military experience; years of airline experience; years of general aviation experience; other.

The overnight cargo crewmembers were 5.4 yr younger on average and had 9.4 yr less experience in their present airline (a minimum estimate of how long they had been flying overnight cargo operations). There were no significant differences between the two groups in their height or weight, or in their scores on the personality inventories.

The average daily percentage sleep loss (including all sleep episodes and naps) was not significantly different during the two types of operations (two-group *t*-test, $t = -0.24$, $p = 0.81$). However, this statistic ignores whether the total sleep was obtained in one or several sleep episodes. **Fig. 6** compares the percentages of crewmembers reporting more than one sleep or nap per 24 h on daytime short-haul fixed-wing and helicopter operations (11,17) and overnight cargo operations. The particularly low incidence of multiple sleep episodes during the daytime short-haul fixed-wing operations is attributable to long duty days and short nighttime layovers which rarely allowed sufficient time for second sleep episodes or naps.

Table XIII compares the incidences of the three symptoms most commonly reported by overnight cargo flight crewmembers and daytime short-haul fixed-wing and helicopter flight crewmembers. The recurrence of the same four symptoms in each type of operation is notable given that the table of symptoms included 20 common complaints.

The responses of 41 overnight cargo and 90 daytime short-haul fixed-wing crewmembers were also compared on questions relating to: general health; increase in gastrointestinal problems on trips; appetite and dietary changes on trips; and effects of fatigue on performance (14). It was hypothesized that responses to these questions might change systematically with age. Therefore, two-way ANOVAs (operation by age) were carried out, with 5-yr age bins from 30–50, and over 50-yr-olds. The only significant finding was that overnight cargo crews reported a slight decrease in appetite on trips, whereas short-haul crews reported no change ($F = 5.84$, $0.05 > p > 0.01$). There were no significant age-related changes in the responses to these questions.

Overnight cargo crews did not increase their daily caffeine consumption during trips, in contrast to daytime short-haul crews (12,15). Both groups consumed a comparable amount of caffeine across the stages of the study (two-way ANOVA, comparing consumption on pretrip, trip, and posttrip days across the two studies: F for the overnight cargo/short-haul comparison $= 0.01$, $p = 0.95$).

DISCUSSION

This study is the first extensive documentation of the psychophysiological effects of flying overnight cargo operations, which represent a growing sector of commercial aviation worldwide. During daytime layovers, individual sleep episodes were about 3 h shorter than when crewmembers were able to sleep at night (i.e., pretrip, on the no-duty day, and posttrip). Crewmembers were three times more likely to report multiple sleep episodes (including naps) on duty days than on non-duty days (53% vs. 17%). Nevertheless, these additional sleep episodes were insufficient to prevent most crewmembers accumulating a sleep debt across trip days. Some 53% averaged more than 1 h of sleep loss on trip days, and 29% averaged more than 2 h of sleep loss. In the laboratory, reducing nighttime sleep by this amount produces cumulative reductions in alertness and performance (4,5). Reducing nighttime sleep in the laboratory by more than 2 h also causes changes in sleep architecture which indicate insufficient sleep (5). In addition to sleeping less on duty days, crewmembers also reported that their daytime sleep was lighter, less restorative, and poorer overall than nocturnal sleep. In contrast, reducing nighttime

TABLE IX. CONSUMPTION OF CAFFEINE, MEALS AND SNACKS ON PRETRIP, DUTY, NO-DUTY, AND POSTTRIP DAYS.

	Mean Pretrip	Mean Duty	Mean No-Duty	Mean Posttrip	F
Caffeine, cups/day	2.06	2.40	2.21	1.76	2.55
Meals/day	2.67	2.48	2.76	2.01	9.02***
Snacks/day	0.78	1.36	0.94	0.61	10.18***

*** $p < 0.001$.

TABLE XI. DUTY CHARACTERISTICS, OVERNIGHT CARGO VS. DAYTIME SHORTHAUL OPERATIONS.

	Mean (SD) Overnight Cargo	Mean (SD) Short-Haul	t
Local time on duty (h)	23.71 (3.53)	8.73 (2.96)	27.11***
Local time off-duty (h)	6.87 (3.01)	19.37 (2.94)	40.54***
Daily duty duration (h)	7.14 (3.69)	10.64 (2.19)	11.67***
Layover duration (h)	14.87 (3.79)	12.52 (2.52)	6.31***
Flight hours/day	2.55 (1.00)	4.50 (1.39)	14.93***
Flight segments/day	2.78 (1.30)	5.12 (1.34)	14.34***
Flight segment duration	0.90 (0.42)	1.07 (0.47)	7.26***

*** $p < 0.001$.

sleep in the laboratory results in shorter sleep latencies and deeper sleep with fewer awakenings (5). If sleep quality was indeed compromised, as the subjective ratings suggest, then this would be expected to further reduce subsequent alertness and performance, in addition to the effects of sleep loss (33).

The night off was used effectively by crewmembers to recuperate some of the sleep loss accumulated as a result of flying at night. They averaged 41 min more sleep per 24 h than pretrip and 115 min more than during daytime layovers. The night off was also strategically placed in the sequence of night duties. On Trip Pattern 1, it was clearly prudent not to add a fourth consecutive night of flying when two-thirds of the crewmembers were averaging more than 2 h of sleep loss per 24 h after 3 nights of flying. In contrast, on Trip Pattern 2, only one-third of the crewmembers were averaging more than 2 h of sleep loss per 24 h by the time of the night off, after 5 nights of flying. The average sleep debt accumulated by the end of the two 8-d patterns was not significantly different (14). Inter-individual variability in sleep loss

TABLE XII. PILOT CHARACTERISTICS, OVERNIGHT CARGO VS. DAYTIME SHORTHAUL OPERATIONS.

	Overnight Cargo Mean (SD)	Short-Haul Mean (SD)	t
Age (yr)	37.62 (4.76)	43.02 (7.65)	3.82***
Experience (yr)	12.79 (4.35)	17.07 (6.56)	3.57***
Present airline (yr)	4.74 (4.17)	14.41 (8.49)	6.60***
Height (in)	70.21 (2.82)	70.59 (1.86)	0.73
Weight (lb)	178.40 (28.29)	174.84 (16.84)	0.69
Eysenck Personality Inventory			
Neuroticism	5.09 (3.91)	6.58 (4.51)	1.49
Extraversion	11.00 (3.89)	10.91 (3.46)	0.11
Lie	3.56 (1.94)	3.41 (1.92)	0.34
Morning/Eveningness Questionnaire	54.44 (7.86)	57.64 (8.67)	1.68
Personal Attributes Questionnaire			
Instrumentality	24.50 (3.96)	23.27 (3.94)	1.36
Expressivity	22.94 (3.85)	22.34 (4.40)	0.63
i + e	3.18 (0.99)	2.84 (1.01)	1.46
Work and Family Orientation			
Mastery	21.30 (3.64)	19.95 (4.10)	1.50
Competitiveness	13.15 (4.08)	12.57 (3.49)	0.67
Work	18.24 (1.63)	17.66 (2.09)	1.32

*** $p < 0.001$.

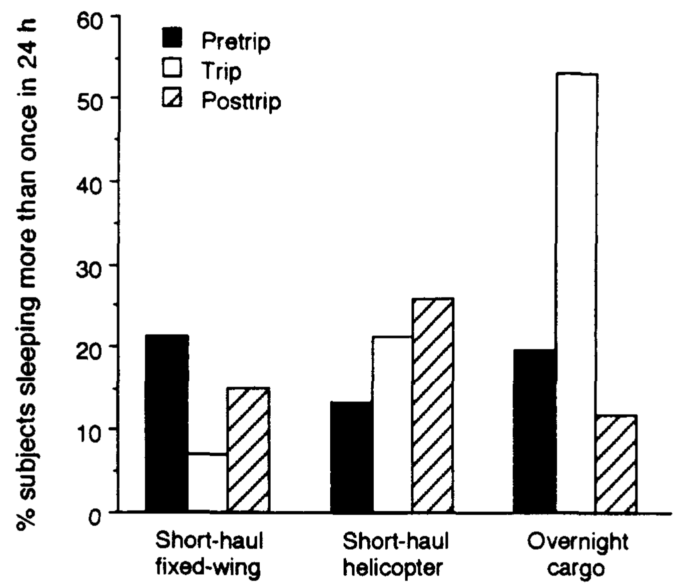

Fig. 6. Percentage of crewmembers reporting more than one sleep or nap episode per 24 h on pretrip, trip, and posttrip days. Comparison of the sleep disruption caused by nighttime flying (overnight cargo operations) and daytime flying (short-haul fixed-wing and helicopter operations).

was high and was not correlated with any of the individual attributes reported by others to predict adaptability to shift work and time zone changes, namely the amplitude of the circadian temperature rhythm, morning/eveningness, extroversion, and neuroticism.

The circadian clock apparently did not adapt completely to the reversed work-rest schedule. The daily temperature minimum delayed by about 3 h when crews flew at night, by comparison with pretrip baseline. This concurs with findings from studies of night workers in other industries (e.g., 24,35,37). The mathematical "unmasking" technique (adding 0.28°C to the raw temperature data for each crewmember whenever he was asleep) did not significantly change the estimate of the overall delay in the temperature minimum that was associated with night duty.

When crewmembers went to sleep in the morning, after a night on duty, they tended to wake up at around the same time (average 1413 hours local time), despite the fact that they had usually slept 2–3 h less than on a pretrip night. Anecdotally, they often reported waking spontaneously and not feeling well-rested. These wakeups were clustered about 6 h after the circadian temperature minimum (average masked estimate 0834, averaged unmasked estimate 0808). Similar clustering of wakeups at this time in the temperature cycle has been reported for people waking spontaneously in time-free environments, when they are living subjective "days" which do not match the period of the temperature rhythm (36). This observation has given rise to the notion of a circadian wakeup signal. Whatever its causes, the regularity of the early afternoon wakeup meant that the duration of morning sleep episodes was systematically related to how early a crewmember finished duty (multiple $r^2 = 0.44$, $F = 37.23$, $p < 0.0001$).

TABLE XIII. PERCENTAGE OF CREW MEMBERS REPORTING THE THREE MOST COMMON PHYSICAL SYMPTOMS IN DIFFERENT FLIGHT OPERATIONS.

	1st Symptom	2nd Symptom	3rd Symptom
Overnight Cargo	Headache (59%)	Congested nose (26%)	Burning eyes (18%)
Short-Haul	Headache (27%)	Congested nose (20%)	Back pain (11%)
Helicopter	Headache (73%)	Back pain (32%)	Burning eyes (18%)

Layovers in which crewmembers were able to sleep again in the evening were longer (average length about 19 h), and ended later (around 0200-0300 hours) than layovers in which they only slept in the morning. Taken together, these findings suggest two ways of increasing the amount of sleep that crewmembers can obtain during daytime layovers: a) by getting off-duty earlier, thus allowing more time for sleep before the circadian wakeup signal; and b) by lengthening the layover sufficiently to allow time for a second sleep episode before the next duty period. There is evidence from controlled laboratory studies that an early evening sleep episode can significantly improve subsequent overnight performance on a variety of tasks (28).

One physiological consideration that crewmembers need to be aware of for evening sleep is the so-called "evening wake maintenance zone" (36). This is a time in the circadian cycle when it can be very difficult to fall asleep, even with a moderate sleep debt. It lasts several hours and occurs shortly before the habitual bedtime, or centered about 8 h before the circadian temperature minimum in a time-free environment. The average pretrip bedtime in the present study was about 0030 hours, and 8 h before the temperature minimum on duty days is also around this time. This suggests that crewmembers may have difficulty falling asleep if they do not go to sleep again before about 2200 hours local time.

Fatigue and activation ratings on pretrip days showed similar time-of-day variation in this study to that seen in other field and laboratory studies (10,12,25). Flying at night altered the time-of-day variation in both variables. However, because of the reduction of the data into 4 h time bins, it was impossible to establish with precision the amount of shift from pretrip to duty days. A further complication in interpreting these data arises from the fact that subjective fatigue and activation ratings appear to comprise two components: a circadian variation which parallels the temperature cycle; and a trend associated with time since sleep (25). Both of these components were altered by night duty. Studies of night workers in other industries have found lowest subjective alertness coinciding with the minimum in body temperature (25). In the present study, when crewmembers were flying at night, highest fatigue and lowest activation were observed in the time bin from 0830–1230 hours, i.e., just after the time of the temperature minimum.

The two mood-state variables monitored, positive and negative affect, did not show significant time-of-day variation on pretrip days, but showed significant variation on duty days and posttrip. Both variables indicated more negative mood during nighttime wakefulness on trips than during daytime wakefulness pretrip. This is consistent with other studies which indicate that circadian variation is not always present in measures of mood states, but that negative changes in mood usually occur when the circadian system is disrupted (25).

Overnight cargo crews did not increase their self-reported daily caffeine consumption during trips, in contrast to crewmembers flying daytime short-haul operations (12,15). Used strategically, caffeine can be a useful fatigue countermeasure because it temporarily increases alertness. However, consumed close to bedtime, it has disruptive effects on sleep, including longer sleep latencies, lighter sleep, and more awakenings (3). These two effects may be difficult to balance for overnight cargo crews, whose low point in alertness occurs toward the end of duty, shortly before they want to fall asleep.

The eating habits of overnight cargo crews are of particular interest because of the increased risk of gastrointestinal problems among night workers (37). On duty days, they ate more snacks, although they reported eating the same number of meals per day as at home. Snacking was used to compensate for less satisfying meals, and/or it may have served as a fatigue countermeasure. Anecdotally, crewmembers said that they often snacked "for something to do." They also reported a decrease in appetite on trips, whereas daytime short-haul fixed-wing crews reported no change (15).

Comparing the overnight cargo and daytime short-haul operations studied (12,15) overnight cargo crews worked less per day, averaging 3.5 h less duty, 2.0 h less flight time, and 2.3 fewer flight segments. They also had more hours available per day for sleep (2.4 h longer layovers) and were younger (by an average of 5.4 yr), which might confer some advantage for obtaining adequate sleep. However, these apparent advantages were more than overridden by the physiological disruption associated with night work. Both groups lost a comparable number of hours of sleep per 24 h while they were on duty. In addition, whereas the daytime short-haul crews typically had one consolidated nighttime sleep episode, the daytime sleep episodes of the overnight cargo crews were much shorter and they frequently had split sleep. This is consistent with findings for night workers vs. day workers in other industries (1,6,37). Because of the incomplete adaptation of the circadian clock to night flying, the overnight cargo crews were also working around the circadian low point in alertness and performance (1,26,37). Thus, for the same amount of sleep loss, the overnight cargo crews were at greater risk of making errors than the daytime short-haul crews.

Overnight cargo crews reported more negative mood and greater fatigue on duty days than on non-duty days, in contrast to the daytime short-haul crews who reported no change (after allowing for time-of-day variation in these measures; ref 15). Overnight cargo crews were more than twice as likely to complain of headaches as daytime short-haul crews. Indeed, the incidence of headaches reported by overnight cargo crews approached that reported by helicopter crews who flew daytime air transport operations in cockpits where overheating, poor ventilation, and high levels of vibration were common (10,11). The differences in reports of physical symptoms between overnight cargo and daytime short-haul crews may be another reflection of the greater physiological challenges of night flying.

In summary, flying at night imposes different challenges than flying during the day, particularly because of the incomplete adaptation of the circadian clock to night work. Effective, safe, practical countermeasures to force the clock to adapt to night work have yet to be validated. However, the increasing demand for 24-h operations in many industries is focusing research efforts in this area (e.g., 37). At present, practical recommendations for reducing fatigue among overnight cargo crews must focus on reducing sleep loss. The current study clearly demonstrates that daytime sleep opportunities are not equivalent to nighttime sleep opportunities, and that increasing the duration of a rest period does not necessarily provide a greater amount of time for sleep. These factors should be considered in regulations governing duty/rest limitations.

Scheduling alternatives for minimizing sleep loss are also highlighted by the present study. Finishing night duty earlier permits a longer sleep episode before the circadian wakeup signal, while going back on duty later allows time for a second sleep episode. These two factors could be counterbalanced in schedule design. A night off in the middle of a sequence of night duties can be an effective countermeasure to accumulating sleep debt. It can be used strategically, by relating its position in the sequence to the rate of sleep loss imposed by a given schedule.

The knowledge and coping strategies of individual crewmembers are a key factor in fatigue management. Education programs are available to address these issues (31). For overnight cargo crews, some specific information is important. For example, they need to be aware of the alertness and performance enhancement that can result from some sleep before a period of night duty, and the performance impairment that accompanies prolonged wakefulness, particularly around the circadian low point in the early morning. The existence and timing of the evening wake maintenance zone may impact their ability to sleep in the evening, and the circadian wakeup signal may curtail their daytime sleep. Information on the strategic use of caffeine to temporarily enhance alertness during night flights, without compromising subsequent sleep, could be useful. The importance of good nutrition for night workers should also be emphasized.

ACKNOWLEDGMENTS

This study was made possible by the enthusiasm and dedication of the pilot volunteers, and the airline management. Mike Baetge and Terry Miller provided invaluable assistance as cockpit observers.

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Flight Crew Fatigue V: Long-Haul Air Transport Operations

PHILIPPA H. GANDER, PH.D., KEVIN B. GREGORY, B.S., DONNA L. MILLER, B.A., R. CURTIS GRAEBER, PH.D., LINDA J. CONNELL, M.A., AND MARK R. ROSEKIND, PH.D.

GANDER PH, GREGORY KB, MILLER DL, GRAEBER RC, CONNELL LJ, ROSEKIND MR. *Flight crew fatigue V: Long-haul air transport operations.* **Aviat Space Environ Med 1998; 69(9,Suppl.):B37–48.**

We monitored 32 flight crewmembers before, during, and after 4–9 d commercial long-haul trips crossing up to 8 time zones per 24 h. The average duty day lasted 9.8 h, and the average layover 24.8 h. Layover sleep episodes averaged 105 min shorter than pretrip sleep episodes. However, in two-thirds of layovers, crewmembers slept twice so that their total sleep per 24 h on trips averaged 49 min less than pretrip. Greater sleep loss was associated with nighttime flights than with daytime flights. The organization of layover sleep depended on prior flight direction, local time, and the circadian cycle. The circadian temperature rhythm did not synchronize to the erratic environmental time cues. Consequently, the circadian low point in alertness and performance sometimes occurred in flight. On trip days, by comparison with pretrip, crewmembers reported higher fatigue and lower activation; drank more caffeine; ate more snacks and fewer meals; and there were marked increases in reports of headaches, congested nose, and back pain. Scheduling strategies and countermeasures to improve layover sleep, cockpit alertness, and performance, are discussed.

IN THE MID-1980's, the Fatigue Countermeasures Program at NASA-Ames Research Center conducted a field study to assess fatigue in commercial long-haul flight operations. There are three factors that combine in these operations to produce unique challenges for crewmembers trying to maintain their alertness and performance on the flightdeck: a) long flights; b) non-24 h duty/rest schedules with daytime and nighttime flying; and c) rapid sequences of transmeridian flights.

Because they typically fly much longer segments than their short-haul counterparts, long-haul crews might be expected to be especially prone to the effects of time-on-task fatigue, including reduced vigilance and habituation. These decrements are particularly sensitive to sleep loss (10).They may also be exacerbated by advanced automation which tends to make the crewmember a less active participant in managing the flight, particularly during cruise (21).

Long-haul trips typically involve sequences of long duty days alternating with relatively long layovers (1–2 d) so that duty/rest cycles do not usually follow a 24-h pattern and are beyond the synchronizing limits of the circadian clock (12). This introduces two potential sources of reduced alertness and performance on the flightdeck (15). First, the low point of the circadian cycle may occur in flight. This is the time in the cycle, around the temperature minimum, when performance on laboratory tasks, in flight simulators, and in other 24-h operations is poorest (1,6,23,25,26,38) and sleepiness is greatest (4). Second, layover sleep may be compromised if the preferred part of the circadian cycle for sleep (8,9,37,42) does not coincide with the layover and local night. Restricted sleep duration and poorer quality sleep both decrease subsequent alertness and performance (5,10,30).

Long-haul crewmembers face an additional challenge because consecutive rest periods (layovers) are usually in different time zones. Thus the circadian clock is deprived of its most important 24-h time cues ("zeitgebers") from the environment–a regular pattern of work/rest and social contact, and the day/night cycle (7,40). When the clock is out of step with environmental time, the symptoms of jet-lag are commonly experienced, including sleep and digestive disturbances, reduced mental and physical performance, and mood changes (22,23,41). Jet-lag has been most extensively studied after single transmeridian flights (18,20,23,24,41). The rate of adaptation of circadian rhythms to a new time zone depends on: the rhythm being studied; the number of time zones crossed; the flight direction, with adaptation being faster after westward flights; and the strength of the geophysical and social zeitgebers experienced in the new time zone.

The effects of rapid sequences of transmeridian flights are not as well documented. Buck and co-workers (2) compared wrist activity during sleep from 30 cockpit and cabin crew before and after three scheduled trip patterns (south-north across 1 time zone: west-east polar route crossing 17 time zones; and east-west across 7 time zones). Only the 11-d polar route (Zurich via Anchorage to Tokyo, and return) resulted in more restless sleep posttrip. A similar 7-d polar route (crossing 16 time

From the Fatigue Countermeasures Program, NASA-Ames Research Center, Moffett Field, CA; San Jose State University Foundation (P. H. Gander); Sterling Software, Inc. (K. B. Gregory, D. L. Miller); Boeing Commercial Airplane Group (R. C. Graeber); and NASA-Ames Research Center (L. J. Connell, M. R. Rosekind).

Address reprint requests to: Philippa H. Gander, Ph.D., who is currently a professorial research fellow in the Department of Public Health, Otago University at Wellington School of Medicine, P.O. Box 7343, Wellington South, New Zealand.

zones, from London via Anchorage to Tokyo, and return) was studied by Spencer and co-workers (36), who monitored subjective and objective sleep measures, subjective alertness, and the circadian temperature rhythm in 12 flight crewmembers. On the outward leg, the two successive extended days were accompanied by accumulating sleep debt, whereas tiredness by the end of the return leg was linked to circadian disruption. Throughout the trip, the temperature rhythm was of low amplitude and out of synchronization with the sleep-wake cycle and the local day/night cycle. Resynchronization of all measures was apparently completed by the sixth day back in London. This study documented major individual differences in the rate and direction of adaptation of circadian rhythms and in sleep patterns and the accumulation of sleep debt. Samel et al. (33) found an effect of layover duration in a study of subjective sleep reports from 101 flight crewmembers on 7 different polar route schedules (Frankfurt via Anchorage to Tokyo or Seoul, and return) lasting 7–11 d. The sleep debt that crews accumulated during the trip was reduced when they remained for longer periods at the destination layover. Presumably, sleep improved as the circadian clock adapted to local time. However readaptation on return to Frankfurt was also slower when crewmembers stayed longer at the destination layover. A polar route in the opposite direction (crossing 16 time zones, from Tokyo via Anchorage to London, and return) was studied by Sasaki and co-workers (35), who recorded subjective and objective sleep measures and subjective alertness from 12 crewmembers. The majority of crewmembers accumulated a significant sleep debt across the 6-d trip, despite napping and spending more time in bed during layovers than pretrip. Recovery was not completed in the 2 nights after their return home. The changes in sleep reflected the effects of prolonged wakefulness during night flights, and, particularly on the home-bound trip, the gradual drifting of the circadian clock away from home (Tokyo) time.

For the NASA long-haul fatigue field study, four trip patterns lasting 4–9 d were selected from the monthly bid packages of the participating airline. They were chosen to be representative of commonly occurring patterns (i.e., westward outbound; eastward outbound; over-and-back transatlantic flights; and primarily north-south displacement, but with long flight times approximating those of the other patterns).

METHODS

The 32 male flight crewmembers who volunteered to participate were flying Boeing 747–200/300 aircraft and were monitored before, during, and after one of the four trips shown in **Fig. 1**. The San Francisco-London pattern was distinctive in that crews returned to their home time zone on alternate layovers. Crews on the Singapore, London, and Auckland trips were domiciled in San Francisco, while those on the Bombay trip were domiciled in New York. Crewmembers had spent at least 4 d in the domicile time zone before entering the study. All data were collected on Greenwich Mean Time (GMT). Characteristics of the trips are summarized in **Table I**. Data for duty times and layover durations were taken from the daily logbooks kept by crewmembers. Data for flight

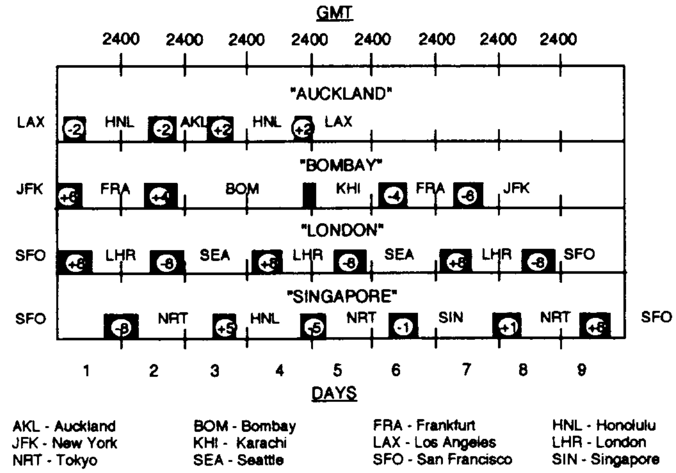

Fig. 1. Timelines of the four trips studied. Black bars indicate flights. Numbers in circles indicate the number of time zones crossed (negative values indicate westward flights; positive values indicate eastward flights).

hours, number of segments, and segment duration, were from the cockpit observer logs (14). Crewmembers flew 1–2 segments per duty day, averaging 6.8 h of flight time and 9.8 h on duty. The average layover across the duty patterns lasted 24.8 h.

To be included in the analyses, crewmembers had to have provided complete logbook data for at least one pretrip day, all trip days, and at least two posttrip days. Some 25 crewmembers (78% of the participants) provided data which met these criteria. Their distribution among the different trips and crew positions is shown in **Table II**. Their average age was 52.7 yr (SD 5.0 yr) and they had an average of 22.8 yr of airline experience (SD 7.6 yr).

Unless otherwise stated, all analyses of variance were within subjects. For t-tests, where a Levene's test revealed unequal variances, the separate t-test value was taken. Otherwise, the pooled t-test value was taken.

In addition to the logbook measures of fatigue, in this study particular attention was focused on effects of duty demands on the circadian clock. In keeping with current convention, the core temperature rhythm (measured at 2-min intervals) was used to monitor the position of the clock. To estimate the period of the clock across trip days, each crewmember's temperature data were subjected to linear-nonlinear least squares interative spectral analysis (31), which searched for significant periodicities in the range 2–40 h, at 0.25 h increments. A significant fit indicated that the fitted sinusoid had a non-zero amplitude ($p < 0.05$). There were 22 subjects (69%) who provided sufficient continuous temperature data for these analyses.

Times of the cycle-by-cycle temperature minima were also estimated. To minimize contamination of these estimates by the short-term temperature changes caused by changes in the level of physical activity, a constant (0.28 C°) was added to the raw temperature data for each subject whenever he was asleep. This mathematical "unmasking" procedure was based on the reported 0.28°C difference between the temperature rhythm during sleep and wake in internally desynchronized people (39).

TABLE I. TRIP STATISTICS (MEAN, RANGE).

	Auckland	Bombay	London	Singapore
Daily duty duration (h)	8.2 (6.1–9.9)	9.1 (3.2–13.2)	11.7 (11.0–12.6)	10.3 (8.4–12.1)
Layover duration (h)	20.2 (11.9–24.4)	29.0 (18.4–48.2)	23.8 (20.0–29.1)	26.1 (23.3–28.8)
Flight hours/duty day	6.5 (4.4–8.4)	5.4 (1.4–8.2)	9.3 (8.5–10.7)	5.8 (2.8–10.2)
Segments/duty day	1.0	1.2 (1–2)	1.0	1.3 (1–2)
Time zones/duty day	2.0	3.6 (0–6)	8.0	4.0 (1–8)
Segments/trip	4.0	6.0	6.0	8.0
Time zones/trip	8.0	18.0	48.0	28.0

Masked and unmasked temperature data for each crewmember were averaged in 20-min bins and subjected to multiple complex demodulation (27). The cycle-by-cycle temperature minimum was taken as the computer-selected lowest value within 12 h in the remodulated waveform. If this procedure identified two minima in 24 h, then the data and the remodulated waveform were superimposed on the sleep and nap times. If there was no clear way of discriminating between the minima (circadian or masking), then the data for that cycle were discarded. Missing points in the raw data were replaced by linear interpolation, and all the fitted waveforms were overlaid with the original data to check that the interpolation did not introduce spurious estimates of minima. A detailed description of the effects of the unmasking procedure on the estimation of circadian parameters is contained in reference 17.

RESULTS

Sleep on Pretrip, Trip, and Posttrip Days

In the daily logbooks it was possible to record up to two sleep episodes and two naps per 24 h, and sleep patterns on layovers were complex and varied. As a first comparison, **Table III** presents the duration and quality of individual sleep episodes on pretrip, trip, and posttrip days*. The probabilities in Table III indicate values for the pretrip/trip/posttrip comparisons in one-way analyses of variance (ANOVA) with subjects treated as random variable. Where ANOVA revealed significant differences, post hoc *t*-tests were used to compare pretrip, trip, and posttrip values. All the comparisons discussed were significant at least at the 0.05 level.

TABLE II. CREWMEMBERS STUDIED ON EACH TRIP PATTERN.

Trip Pattern	Captains	First Officers	Flight Engineers	Total
Auckland	2	1	1	4
Bombay	2	1	1	4
London	3	3	3	9
Singapore	3	2	3	8
Total	10	7	8	25

* Sleep latency was calculated as the difference between the reported times of going to bed and falling asleep. Scores on the four sleep quality questions (rated from 1-least to 5-most) were converted so that higher values indicated better sleep, and combined to give the overall sleep rating. Heart rate and activity data during each sleep episode were trimmed to include values from 20 min after the reported sleep onset time until 10 min before the reported wakeup time (14).

Sleep episodes during layovers were shorter than those either pretrip or posttrip. Sleep episodes on posttrip days were shorter than those on pretrip days, and tended to be deeper ($t = 1.80$, $p = 0.08$). Overall, crewmembers reported significantly less sleep per 24 h during trips than either pretrip or postrip. Consequently, they accumulated a sleep debt across the days of the trip.

This is illustrated in **Fig. 2**. For each subject, daily sleep loss (or gain) was calculated by subtracting the total sleep per 24 h (including naps) from his average total sleep per 24 h on pretrip days. The sleep loss (or gain) on consecutive trip days was added to produce the cumulative sleep loss curve. Curves for all the subjects on each trip pattern were then averaged together. The zigzag patterns in the sleep loss curves for the London and Singapore trips are the result of sleep loss after night flights (sharp rises) vs. recuperation (flattening or decline) after daytime flights. Usually the night flights were eastward flights across four or more time zones. However, on the Singapore pattern, the increase in sleep loss on day 6 followed a flight from Nerita (Japan), via Hong Kong, to Singapore, crossing one time zone west and arriving in the middle of the local night. There was considerable variability in sleep loss between crewmembers, and between the trip patterns. This is examined further in **Table IV**.

Considering the total sleep loss per 24 h is somewhat misleading in these operations, because duty days were associated with extended periods of wakefulness (mean 20.6 h, maximum 35.8 h), whereas layovers often included two sleep episodes and a much shorter period of wakefulness. Recall that the average cycle of one-duty-period-plus-one-rest-period was about 35 h (Table I).

Influence of Prior Flight Direction on Layover Sleep

Examination of the sleep/wake records of individual crewmembers revealed that three basic sleep patterns together accounted for 97% of layovers (excluding the 48 h layover on the Bombay trip and the 12 h layover on the Auckland trip). Crewmembers either: slept once (29% of layovers); or had a longer sleep episode followed by a shorter sleep episode (26% of layovers); or had a shorter sleep episode followed by a longer sleep episode (42% of layovers). These sleep patterns are related to prior flight direction in **Fig. 3**, which includes data from 122 layovers. After westward flights crossing four or more time zones, the first sleep episode was usually long (83% of cases), and was followed in 50% of cases by a second shorter sleep episode toward the end of the layover. Conversely, after eastward flights crossing four or more time zones, in nearly 70% of cases crewmembers

TABLE III. COMPARISONS OF INDIVIDUAL SLEEP EPISODES BEFORE, DURING, AND AFTER TRIPS (MEANS).

	Pretrip	Trip	Posttrip	p(F)
Sleep onset (GMT)	7.30	12.69	10.76	***
Wakeup (GMT)	14.74	13.05	13.70	***
Sleep latency (min)	31.73	33.88	37.39	
Sleep duration (h)	7.08	5.33	6.00	***
Total sleep/24 h	7.29	6.48	8.01	***
Difficulty falling asleep?	3.79	4.07	4.06	
How deep was your sleep?	3.15	3.51	3.52	*
Difficulty rising?	3.67	3.45	3.53	
How rested do you feel?	3.26	2.90	3.11	
Sleep rating	13.87	13.93	14.13	
# Awakenings	1.02	0.71	1.07	
Heart rate during sleep	62.75	64.64	63.56	
Variability in heart rate during sleep	6.10	6.23	6.41	
Activity during sleep	1.91	3.21	3.20	
Variability in activity during sleep	6.89	7.03	7.83	
Temperature during sleep	36.34	36.35	36.28	
Variability in temperature during sleep	0.16	0.13	0.13	

* $0.05 > p > 0.01$; *** $p < 0.001$.

took a short sleep soon after arrival at the layover, followed by a longer sleep later in the layover. After flights crossing fewer than four time zones, the three sleep patterns occurred with approximately equal frequency.

To test whether the total amount of sleep obtained in a layover was dependent on prior flight direction, between subjects one-way ANOVAs were carried out **(Table V)**. There were no significant differences in either the total number of hours of sleep that crewmembers were able to obtain, or in the percentage of the layover time that they spent asleep, after flights crossing four or more time zones west vs. east vs. flights crossing fewer than four time zones.

Within subjects one-way ANOVAs were also carried out separately for the Bombay, Singapore, and London trips. These confirmed that prior flight direction did not have any consistent effect on the total amount of sleep that crewmembers were able to obtain in a layover. (On the Auckland trip, all layovers followed flights crossing fewer than four time zones.) Taken together, these analyses suggest that preceding flight direction influenced how crewmembers organized their layover sleep, but not how much sleep they were able to obtain.

To test whether the duration of continuous wakefulness was different for different flight directions, a one-way between-subjects ANOVA was performed (Table V).

Tukey post hoc tests with Bonferroni correction revealed that duty days which included flights crossing fewer than 4 time zones involved significantly ($p < 0.01$) shorter wake durations than duty days including flights crossing 4 or more time zones, either westward or eastward.

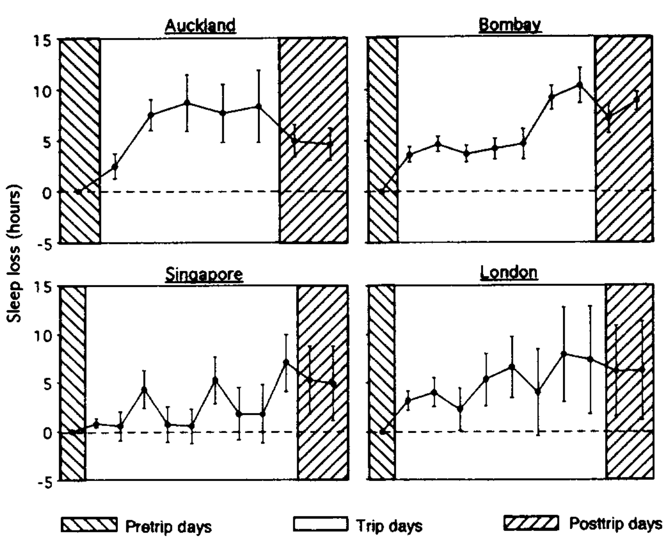

Fig. 2. Average day-by-day cumulative sleep loss with respect to baseline sleep, on each of the trip patterns. For each subject, his total sleep per 24 h on each trip day was subtracted from his average total sleep per 24 h on pretrip days, to give a daily measure of sleep loss. Average daily sleep loss was then calculated, and the values added across the consecutive trip days and posttrip days.Vertical bars indicate standard errors.

Influence of Local Time on Layover Sleep

In the Background Questionnaire (14) crewmembers were asked to describe their strategy after multiple time zone crossings on a scale from 1 (stick to home time) to 5 (shift to local time), and to rate how successful they thought their strategy was on a scale from 1 (very effective) to 5 (not at all effective). The distributions of their responses are shown in **Fig. 4**. Responses on the two questions were not significantly correlated. The majority of crewmembers tended to try to adapt to local time. Overall they felt that their strategies were only moderately successful (average 2.5).

Fig. 5 shows the distributions of layover sleep episodes with respect to local time. There was a clear preference for sleeping during local night, with a secondary preferred sleep time in the local afternoon. The majority of afternoon sleep episodes were short and followed eastward night flights crossing four or more time zones (12). They also appear as the secondary late-afternoon peak in the distribution of wakeups with respect to local time in the lower half of Fig. 5.

Circadian Adaptation

Of the 22 subjects providing continuous temperature data, 18 (82%) showed significant circadian variation

TABLE IV. PERCENTAGES OF SUBJECTS GAINING AND LOSING SLEEP ON THE FOUR TRIP PATTERNS.

	Auckland	Bombay	London	Singapore
% subjects gaining sleep	0	0	33	11
% subjects >1 h loss/24 h	60	80	33	22
% subjects >2 h loss/24 h	20	20	33	11
	n = 5	n = 5	n = 9	n = 9

Note: Three additional crewmembers were included in these analyses (c.f. Table II). They provided pretrip and trip sleep data, but no posttrip sleep data.

across trip days, with an average period of 25.7 h (SD 1.27 h). One subject from each of the four trip patterns showed no significant circadian periodicity in core temperature across trip days. One consequence of the failure of the circadian clock to synchronize to the duty/rest cycle was that the temperature minimum sometimes occurred in flight. This is shown for the Auckland, London, and Singapore trips in **Fig. 6**. (Only one subject gave complete data on temperature minima during the Bombay trip).

The circadian times of layover sleep episodes were calculated on a cycle-by-cycle basis by subtracting the GMT time of the nearest temperature minimum from the GMT times of sleep onset and wakeup. This was done for both masked and unmasked estimates of the times of the temperature minima. **Fig. 7** shows the distributions of layover sleeps with respect to the circadian cycle. For the unmasked data, the average sleep onset time was 2 min after the temperature minimum, and the average wakeup time was 6.4 h after the temperature minimum. This is comparable to the circadian distributions of sleep onset and wakeup when people living in time-free environments adopt subjective "days" that are different from the period of the circadian temperature rhythm (37). There were 13 sleep episodes (10%) that ended as the masked temperature was falling, or around the time of the unmasked temperature minimum. These sleep episodes, which were short and occurred right at the end of layovers, were probably terminated because crewmembers had to get up to go on duty, rather than in response to physiological factors (12).

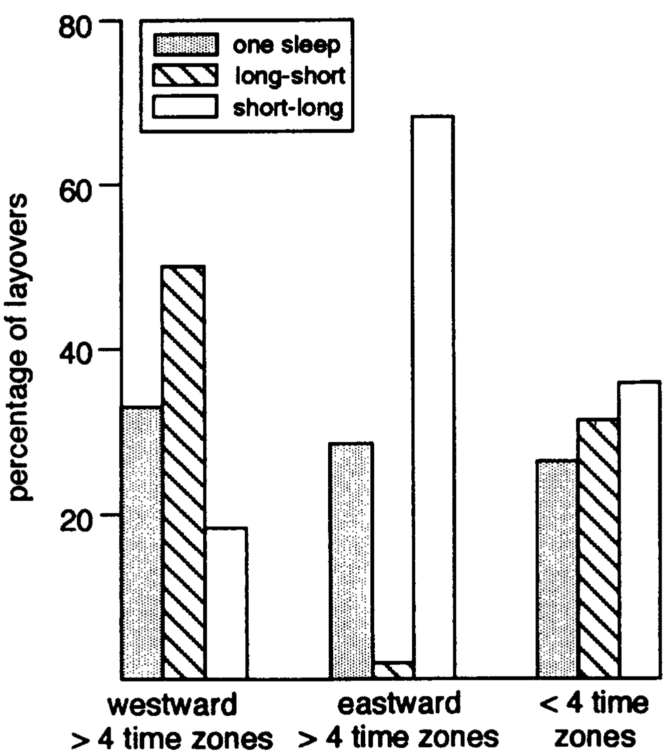

Fig. 3. Layover sleep patterns vs. prior flight direction. Flights crossing less than four time zones in either direction have been grouped together. Long-short indicates layovers in which the first sleep episode was long and the second short. Short-long indicates layovers in which the first sleep episode was short and the second long.

Fatigue and Mood Ratings

Every 2 h while they were awake, subjects rated their fatigue levels on a 10 cm line from "most alert" to "most drowsy" and rated their current mood from 0 (not at all) to 4 (extremely) on 26 adjectives. These adjectives have previously found to load on three orthogonal factors, designated "positive affect," "negative affect," and "activation" (13). One-way ANOVAs, with subjects treated as a random variable, were carried out to see if the ratings varied significantly on pretrip days **(Table VI)**. There were 20 subjects who provided sufficient data, which were converted to local time for these analyses.

On pretrip days, ratings of fatigue, negative affect, and activation showed significant time-of-day variation similar to that observed pretrip in other studies (11,15,16). Positive affect did not show significant time-of-day variation pretrip.

Because the duty-rest schedule did not follow a 24 h pattern, and the circadian clock was drifting with respect to environmental time during trips, crewmembers were rating themselves at different times during the circadian cycle on trips vs. pretrip. It is thus impossible to separate out the effects of duty from the effects of sampling a different part of the circadian cycle. To obtain an overall comparison, fatigue and mood ratings made on trips were compared with those pretrip. Data were available for 18 subjects. One-way ANOVAs, with subjects treated as a random variable, indicated that fatigue on trips was significantly higher ($F = 12.67$, $p < 0.01$) and activation was significantly lower ($F = 5.03$, $p < 0.05$). Positive and negative affect did not change significantly on trips by comparison with pretrip.

Caffeine, Meals, and Snacks

Caffeine was available in-flight as well as on the ground. In their daily logbooks, crewmembers recorded the number of cups of caffeinated beverages that they

TABLE V. TOTAL SLEEP AND DURATION OF CONTINUOUS WAKEFULNESS (MEAN ± SD) AS A FUNCTION OF FLIGHT DIRECTION.

	West > 3	East > 3	<4	F
# of hours asleep	9.43 (2.63)	9.14 (2.98)	8.96 (2.78)	0.24
% of layover asleep	35.78 (8.04)	40.51 (11.49)	38.95 (8.27)	2.14
	n = 31	n = 36	n = 36	
Wake duration (h)	21.32 (3.79)	22.74 (6.75)	17.59 (3.81)	17.56****

**** $p < 0.0001$.

drank and the time of day (GMT) at which they drank them. Caffeine was consumed by 92% of subjects at some time during the study. To test if duty demands had an effect on caffeine consumption, a one-way ANOVA was performed, with subjects treated as a random variable **(Table VII)**.

Crewmembers drank significantly more caffeine per 24 h on trips than either pretrip ($t = -2.63$, $0.05 > p > 0.01$) or posttrip ($t = 2.24$, $0.05 > p > 0.01$).

They also recorded the times that they ate and the classification of meals (breakfast, lunch, dinner, snack) in the daily logbook. To test whether duty demands had an effect on the number of meals or snacks eaten per 24 h, one-way ANOVAs were performed, with subjects treated as a random variable (Table VII). These analyses include data for 24 subjects. Crewmembers ate significantly fewer meals per 24 h on trips than pretrip ($t = 2.28$, $0.5 > p > 0.01$) and they ate more snacks per 24 h on trips than either pretrip ($t = 3.03$, $p < 0.01$) or posttrip ($t = 4.37$, $p < 0.0001$).

Physical Symptoms

The logbook contained a table for each day noting physical symptoms (14). Some 80% of crewmembers indicated that they had experienced at least one of the 20 symptoms at some time during the study. The three most common symptoms were: headaches (reported by 56% of subjects at some time during the study); congested nose (reported by 28% of subjects at some time during the study); and back pain (reported by 20% of subjects at some time during the study). The frequency of reports of each of these symptoms on pretrip, trip, and posttrip days is shown in **Table VIII**.

The incidence of reports of headaches increased 2.7-fold on trips by comparison with pretrip, while the incidence of congested nose increased 17.2-fold, and the incidence of back pain increased 7.5-fold.

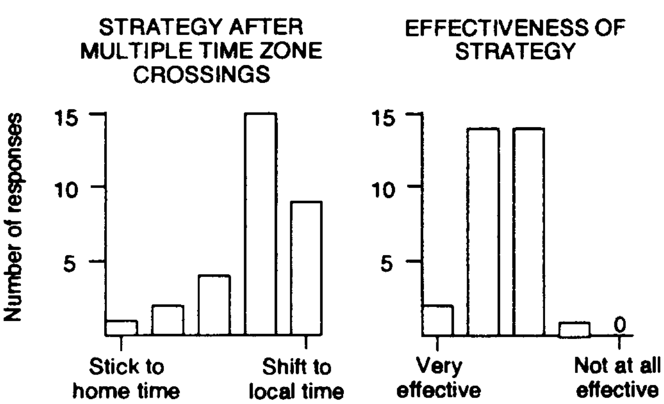

Fig. 4. Distributions of responses to two questions on crewmember strategies after time zone shifts.

Comparisons With Daytime Short-Haul Fixed-Wing Operations

Table IX compares (by 2-group t-tests) the duty characteristics of the long-haul operations with those of the daytime short-haul fixed-wing operations described in the second paper of this series (16). The short-haul statistics are for the subset of trips flown by the 44 subjects included in the sleep analyses in (16).

The two groups had duty days of comparable length, however the long-haul crewmembers usually flew only one segment which was longer, on average, than the total daily flight time of the short-haul crews who flew up to

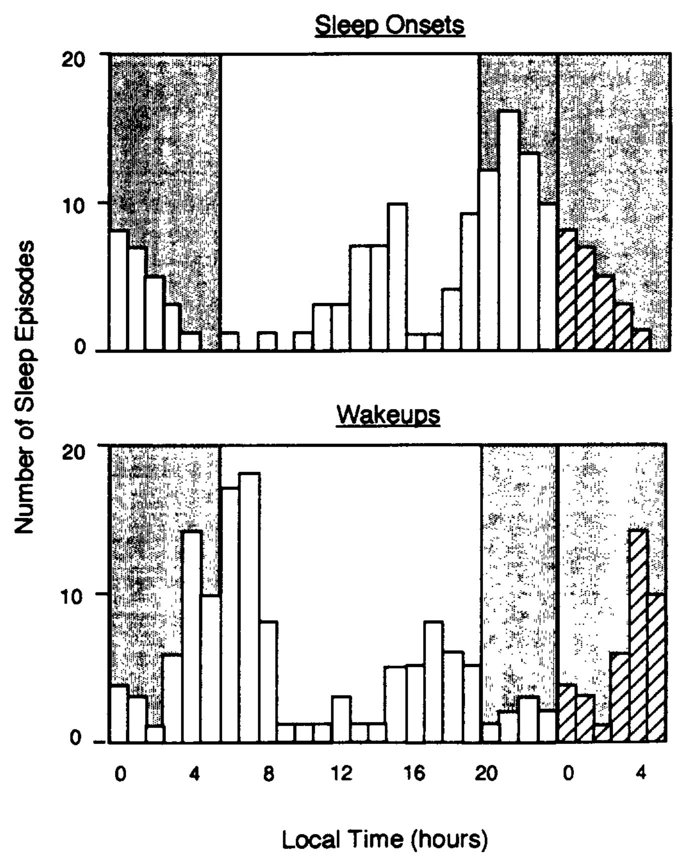

Fig. 5. Distributions of layover sleep onsets and wakeups with respect to local time. Shading indicates approximate times of local night. The first 6 h of data are repeated (cross-hatched columns), to emphasize the cyclic nature of the pattern.

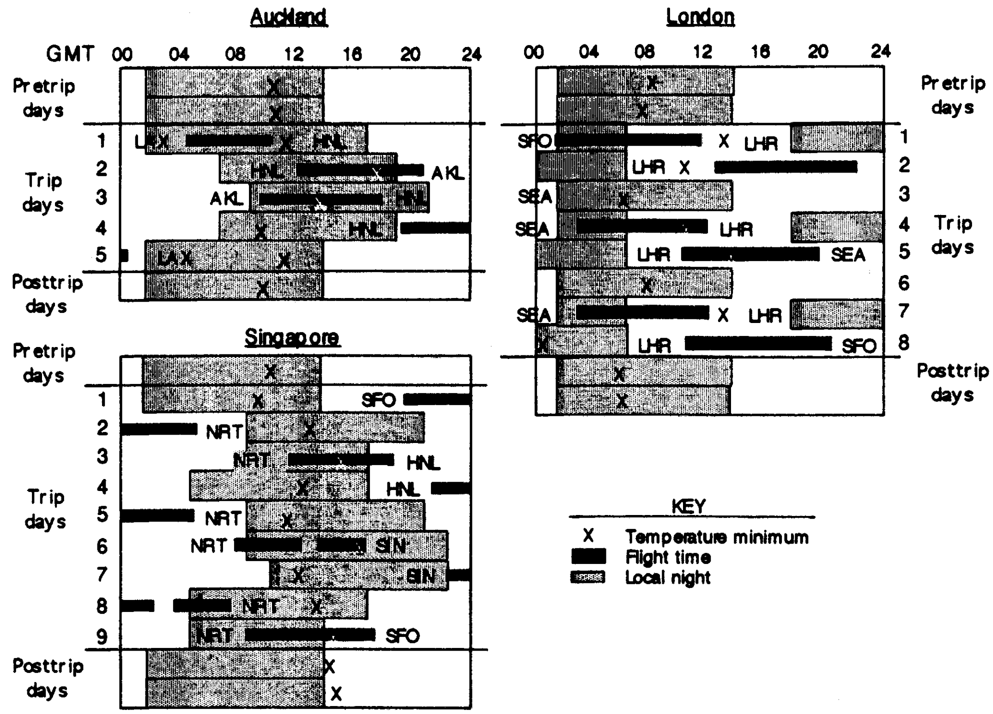

Fig. 6. Average times of the unmasked daily temperature minima on the Auckland trip pattern (average of three subjects per day), the London trip pattern (average of four subjects per day), and the Singapore trip pattern (average of six subjects per day).

8 segments per day. Long-haul layovers were twice as long. Long-haul operations also included both daytime and nighttime flying, and crossed up to 8 time zones per 24 h, whereas the short-haul operations included primarily daytime flying and crossed no more than one time zone per 24 h.

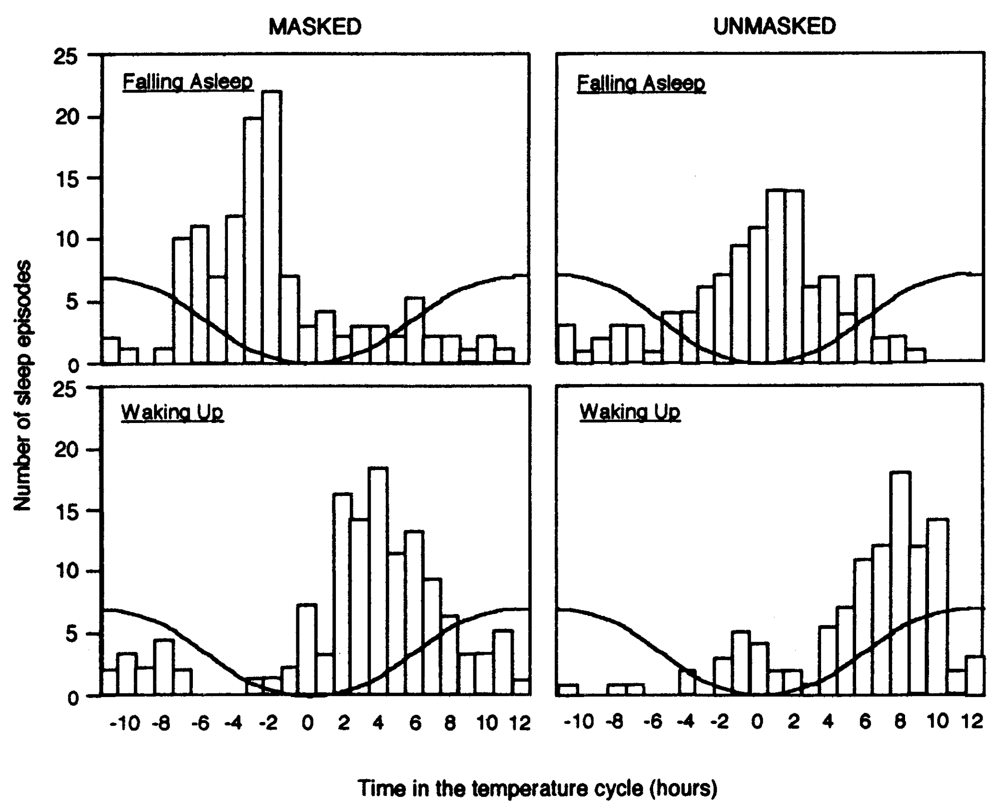

Fig. 7. Distributions of layover sleep onsets and wakeups plotted with respect to the temperature rhythm (shown schematically), for both masked and unmasked estimates. The temperature minimum has been designated circadian time zero.

TABLE VI. TIME-OF-DAY VARIATION IN PRETRIP FATIGUE AND MOOD RATINGS.

	Mean, 0800–1200 Hours	Mean, 1200–1600 Hours	Mean, 1600–2000 Hours	Mean, 2000–2400 Hours	F
Fatigue	31.12	32.84	41.65	55.28	12.60***
Positive affect	2.45	2.41	2.55	2.40	0.67
Negative affect	0.53	0.52	0.59	0.88	6.49***
Activation	2.51	2.60	2.20	1.61	25.70***

Note: times are GMT hours.

Table X compares (by 2-group *t*-tests) demographic and personality measures for the two groups of crewmembers. This information came from the Background Questionnaires. The years of experience was taken as the largest value from among the following categories: years with the present airline; years of military experience; years of airline experience; years of general aviation experience; other.

The long-haul crewmembers were older, more experienced, and more morning-type than their short-haul counterparts. There were no significant differences between the groups in their height or weight, or in their scores on the personality inventories.

The average daily percentage sleep loss (including all sleeps and naps) was not significantly different during the two types of operations (2-group *t*-test; $t = 0.98$, $p = 0.33$). However, this statistic oversimplifies the sleep changes resulting from duty demands, in that it does not take into account sleep quality or whether the total is obtained in one or several episodes. Considering sleep loss per 24 h is also somewhat misleading in the long-haul operations, because of the non-24 h duty/rest schedule. **Fig. 8** compares the percentages of crewmembers reporting multiple sleep episodes (including naps) on pretrip, trip, and posttrip days, for different flight operations. During trips, long-haul crewmembers slept more than once in a third of all 24 h periods. However, as noted above, they slept twice in about two-thirds of all layovers (68%). This is markedly higher than the incidence of split sleep among the short-haul crews. **Fig. 9** examines the number of hours of sleep per 24 h which came from sleep episodes other than the longest. As expected, long-haul crews had more total sleep per 24 h coming from secondary sleep episodes.

Table XI compares the incidences of the three most common symptoms reported in the different types of operations. The helicopter cockpits were physically stressful, with high levels of vibration, poor ventilation, and high thermal loadings on crewmembers who often wore cold-water immersion suits (11).

The high incidence of back pain among long-haul crews, relative to the short-haul fixed-wing crews, could be due to the long flight segments requiring them to remain in their cockpit seats for much longer periods of time.

The responses of 32 long-haul crewmembers and 31 short-haul crewmembers over 40 yr of age were also compared (by 2-group *t*-tests) on questions from the Background Questionnaire concerning: general health; gastrointestinal problems, appetite, and diet on trips by comparison with home; time taken to return to normal after a trip; and the incidence and severity of fatigue effects on performance (14). Even with this age restriction, the long-haul crewmembers were significantly older (52.5 yr vs. 47.1 yr, 2-group *t*-test, $t = 4.83$, $p < 0.0001$). The only significant difference between the responses of the groups was that long-haul crewmembers reported taking longer to return to normal after a trip (3.2 d vs. 1.9 d, $t = 8.20$, $p < 0.0001$). There was also tendency for long-haul crewmembers to report that fatigue affected their performance more often during a trip than short-haul crewmembers. On a scale from 1 (never) to 5 (frequently), the average score for long-haul crewmembers was 3.17, vs. 2.71 for short-haul crewmembers ($t = 1.81$, $p = 0.08$).

DISCUSSION

The physiological challenges for long-haul crews are exceptionally complex. During the operations studied, the duty/rest cycle forced the sleep/wake cycle to a non-24 h pattern to which the circadian clock could not synchronize. Duty days were associated with long periods of wakefulness (average 20.6 h) while layovers, which averaged 24.8 h, usually included several sleep episodes and shorter periods of wakefulness. Individual sleep episodes during layovers averaged only 5 h 20 min, which was 105 min shorter than sleep episodes on pretrip nights. Comparing the total sleep per 24 h (including naps) on trip days vs. pretrip days, across the four trip patterns studied, 43% of crewmembers averaged more than 1 h of sleep loss on trip days, and 21% averaged more than 2 h of sleep loss. In the laboratory, these levels

TABLE VII. DAILY CONSUMPTION OF CAFFEINE, MEALS AND SNACKS BEFORE, DURING, AND AFTER TRIPS (MEAN, SD).

	Pretrip	Trip	Posttrip	F
Cups of caffeine	1.87 (1.83)	3.14 (1.58)	2.04 (1.88)	9.76***
Number of meals	2.44 (0.57)	2.12 (0.37)	2.28 (0.50)	3.58*
Number of snacks	0.87 (0.80)	1.56 (0.78)	0.67 (0.61)	19.39***

* $0.05 > p > 0.01$; *** $p < 0.001$.

TABLE VIII. FREQUENCY OF REPORTS OF COMMON MEDICAL SYMPTOMS ON PRETRIP, TRIP, AND POSTTRIP DAYS.

Symptom	% Pretrip	% Trip	% Posttrip
Headache	19	52	30
Congested nose	5	86	10
Back pain	11	83	6

TABLE IX. COMPARISON OF DUTY CHARACTERISTICS, LONG-HAUL VS. SHORT-HAUL OPERATIONS.

	Mean (SD) Long-Haul	Mean (SD) Short-Haul	t
Duty duration (h)	10.22 (2.06)	10.66 (2.41)	1.76
Layover duration (h)	24.25 (3.96)	12.52 (2.52)	28.83***
Flight hours/day	6.88 (2.62)	4.50 (1.39)	11.25***
Flight segments/day	1.15 (0.36)	5.12 (1.34)	34.15***
Flight hours/month	69.20 (9.13)	70.21 (9.92)	0.41

*** $p < 0.001$.

of sleep loss produce cumulative reductions in alertness and poorer performance (5,30). On the other hand, 14% of crewmembers reported sleeping more on trips than prettrip. Looking at the total sleep per 24 h probably underestimates the potential impact of sleep loss on cockpit alertness and performance in these operations for three reasons. First, it ignores the fact that crewmembers did not obtain the same amount of sleep in each 24 h period. By the end of a duty day, they often had a large acute sleep debt, particularly after a night flight. However, in the subsequent layover, they tended to sleep more than during a normal 24 h period at home, thereby reducing their average sleep loss per 24 h. Second, it overlooks the cumulative effects of sleep loss across the entire 4–9 d trip. Third, it does not take into account the fact that layover sleep was often split into several short episodes, and was not always during local night or in the preferred part of the circadian cycle, which could have affected its duration and quality (8,9,37,42).

Greater sleep loss was associated with night flights. This was not due to a difference in how long crewmembers remained awake in association with eastbound overnight flights vs. westbound daytime flights. However, it may have been related to greater sleep disruption after eastward overnight flights. Polygraphic recordings of the sleep of long-haul flight crews during the first layover of scheduled international trips indicated that it was more disturbed after eastward night flights crossing 8 time zones than after daytime westward flights crossing 8–9 time zones (20). In the NASA field study of cockpit naps as a fatigue countermeasure in long-haul operations (29), crewmembers reported feeling more fatigued during eastward night flights than during westward daytime flights. Those who were allowed to nap also experienced deeper sleep (confirmed polygraphically) during night flights than during daytime flights.

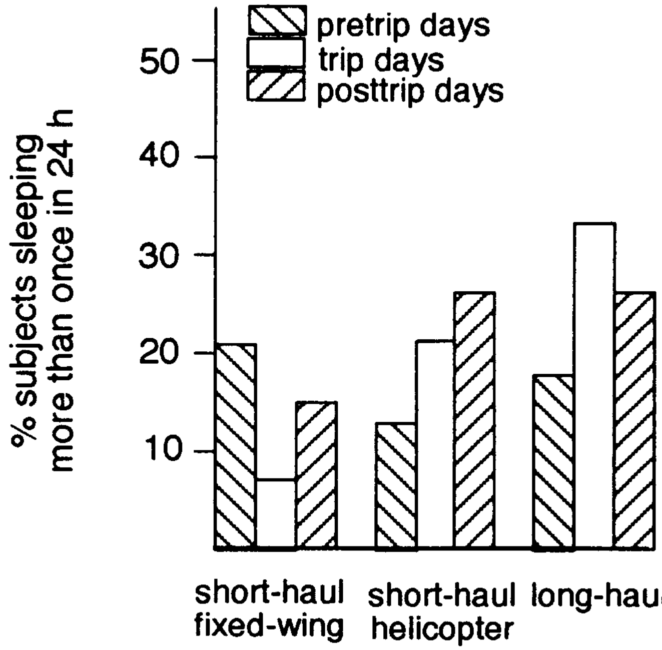

Fig. 8. Comparisons among different operations of the percentages of crewmembers sleeping more than once per 24 h.

When asked about their layover strategies, most crewmembers indicated that they tried to adapt to local time, but considered that they were only moderately successful. It is not surprising that few tried to remain on home time, since this strategy would be incompatible with a 35 h duty-rest pattern. There was a clear preference for sleeping during the local night, with a secondary preferred sleep time in the local afternoon. The majority of

TABLE X. COMPARISON OF CREWMEMBER CHARACTERISTICS, LONG-HAUL VS. SHORT-HAUL OPERATIONS.

	Mean (SD) Long-Haul	Short-Haul	t
Age (yr)	52.68 (4.96)	43.02 (7.65)	5.66***
Experience (y)	22.80 (7.58)	17.07 (6.56)	3.29**
Height (in)	71.00 (2.15)	70.59 (1.86)	0.87
Weight (lb)	181.6 (17.10)	174.84 (2.15)	1.70
Eysenck Personality Inventory (ref. 23)			
Neuroticism	6.63 (3.68)	6.58 (4.51)	0.04
Extraversion	9.44 (4.33)	10.91 (3.46)	1.52
Morning/Eveningness Questionnaire (ref. 24)	67.70 (8.37)	63.41 (9.47)	2.06*
Personal Attributes Questionnaire (ref. 25)			
Instrumentality	22.76 (4.69)	23.27 (3.94)	0.52
Expressiveness	22.09 (3.84)	22.34 (4.40)	0.27
i + e	2.74 (1.19)	2.84 (1.01)	0.42
Work and Family Orientation Questionnaire (ref. 26)			
Mastery	20.67 (4.04)	19.95 (4.10)	0.76
Competitiveness	13.61 (2.94)	12.57 (3.49)	1.38
Work	17.48 (2.25)	17.66 (2.09)	0.35

* $0.05 > p > 0.01$; ** $0.01 > p > 0.001$; *** $p < 0.001$.

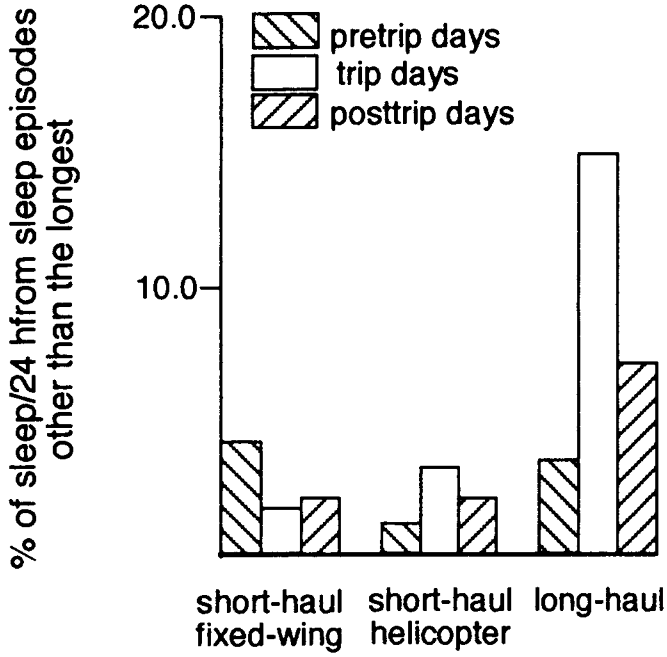

Fig. 9. Comparisons among different operations of the amount of daily sleep accrued from sleep episodes other than the longest.

the afternoon sleep episodes followed eastward night flights crossing four or more time zones. The average off-duty time after these flights was about 1100 hours local time. Two-thirds of crewmembers went to sleep for several hours in the afternoon, and then slept again later in the local night. In contrast, after westward flights crossed four or more time zones, the first sleep episode in the layover was the longest for 80% of crewmembers, and it tended to coincide with local night. The average off-duty time after these flights was around 1400 hours local time.

Crewmembers were most likely to fall asleep around the time of the temperature minimum and to wake up while temperature was rising. Two types of sleep episodes could be identified which were not consistently linked to the preferred part of the circadian cycle. The afternoon sleep episodes after eastward night flights crossing four or more time zones were broadly distributed in the circadian cycle (12), which suggests that they were primarily a response to sleep loss rather than to circadian physiology. In westward flights crossing four or more time zones, 50% of crewmembers took a shorter second sleep toward the end of the layover. Most (85%) of the sleep episodes which ended as temperature was falling (Fig. 7) are of this type. In these cases, it seems likely that crewmembers woke up because of the imminent duty report time, rather than in response to the circadian wakeup signal, which normally occurs about 6 h after the temperature minimum (15,37).

For at least 2 nights after the trip, crewmembers continued to have shorter individual sleep episodes than pretrip (average 65 min less). However, they often slept more than once per 24 h, so that their total sleep duration regained pretrip levels. This continued disruption of the normal pattern of consolidated sleep at night presumably reflects the readaptation of the circadian clock to the home time zone. Long-haul crewmembers reported taking longer to return to normal after a trip than did their daytime short-haul counterparts.

The finding that the temperature rhythm was unable to synchronize to the rapid sequences of time zone changes and non-24 h duty-rest cycles in these operations confirms similar findings for flight crews on polar route schedules between Europe and Japan (32,35,36). As a consequence, the circadian temperature minimum, and hence the low point in alertness and performance (1,10,23,26,30), sometimes occurred in flight (Fig. 6). At the same time, the majority of crewmembers were operating with a sleep debt. In the laboratory, working through the time of the circadian low point with a sleep debt results in lowest alertness and greatest vulnerability to performance errors (10).

From the daily logbooks, and from the cockpit observers' notes, it was ascertained that the crewmembers in this study were asleep in their cockpit seats 11% of the available time (21), in spite of the fact that this is not currently sanctioned by the FAA. High levels of sleepiness on the flightdeck were confirmed polygraphically for three-person long-haul crews on scheduled trans-Pacific flights, in the field test of cockpit napping as a fatigue countermeasure (29). When crewmembers were given a preplanned 40-min opportunity to nap in their cockpit seats, they fell asleep on 93% of the available occasions. They fell asleep quickly (average 5.6 min), which is close to the threshold (5 min) considered to indicate pathological sleepiness in clinical situations. The study also included a control group of crewmembers who were instructed not to nap. On five occasions crewmembers in this group also fell asleep, despite being monitored polygraphically for sleep and having two NASA observers in the cockpit. The high level of sleepiness of the no-rest group was confirmed by the fact that they had five times as many in-flight EEG microevents and poorer probed performance. Of these microevents, which signal transient disengagement from the environment, 22 occurred among no-rest crewmembers during descent into the destination airport.

In the present study, crewmembers rated their subjective fatigue as higher, and their activation as lower, on duty days than on pretrip days. They perceived that fa-

TABLE XI. PERCENTAGE OF CREWMEMBERS REPORTING THE THREE MOST COMMON MEDICAL SYMPTOMS IN DIFFERENT FLIGHT OPERATIONS.

	1st Symptom	2nd Symptom	3rd Symptom
Long-Haul	Headache (56%)	Congested nose (28%)	Back pain (20%)
Short-Haul Fixed-Wing	Headache (27%)	Congested nose (20%)	Back pain (11%)
Short-Haul Helicopter	Headache (73%)	Back pain (32%)	Burning eyes (18%)

tigue had some effect on their performance, with an average rating of 3.4 on a scale from 1 (none) to 5 (very much). They also indicated that, on a typical trip, fatigue sometimes affected their performance, with an average rating of 3.2 on a scale from 1 (never) to 5 (frequently). On trips, they consumed more caffeine and snacks, and fewer meals per 24 h than at home pretrip. The availability of meals at unusual local times is a common problem for long-haul crewmembers, whose duty schedules and hunger patterns do not necessarily coincide with local meal times. The incidence of headaches (reported by 56% of crewmembers during the study) tripled on trip days by comparison with pretrip. The incidence of congested nose (reported by 28% of crewmembers) increased 17-fold, while the incidence of back pain (reported by 20% of crewmembers) increased 7.5-fold.

Comparing these operations with the daytime fixed-wing short-haul operations examined in the first NASA fatigue field study (13,16), the long-haul crews worked duty days of comparable length, but with fewer flights and more flight hours than their short-haul counterparts. Long-haul crews crossed up to eight time zones in a duty day, whereas short-haul crews crossed no more than one. The long-haul crewmembers were older (by an average of 9.7 yr), more experienced (by an average of 5.7 yr), and were more morning-type than their short-haul counterparts. This is consistent with the trend for people to become more morning-type as they get older (19). A number of studies have suggested that morning-types have more difficulty adapting to shift work and time zone changes than evening types (19). One study of commercial long-haul flight crewmembers (34) found that morning types showed higher levels of daytime sleepiness than evening types, after operating an eastward flight crossing eight time zones. Thus, the common practice of promoting crews from short-haul to long-haul operations as they become more senior results in people flying more physiologically challenging operations when normal aging processes dictate that they may be less able to cope with those challenges.

Long-haul layovers were twice as long as short-haul layovers. Both groups lost a comparable amount of sleep per 24 on trips with respect to pretrip. However, this comparison is somewhat misleading because of the non-24 h sleep/wake patterns of the long-haul crews, and the fact that they often slept more than once during layovers averaging 24.8 h. On trips, long-haul crewmembers gained 7.5 times more sleep per 24 h from secondary sleep episodes than did their short-haul counterparts. They also reported higher fatigue and lower activation on duty days by comparison with pretrip days. Comparable changes were not reported by the short-haul crewmembers after allowing for the time-of-day variation in these measures (13,16). Long-haul crewmembers reported headaches and back pain twice as often as their short-haul counterparts. Both groups consumed more caffeine and snacks on trips. However, only the long-haul crewmembers reported eating fewer meals per 24 h on trips by comparison with pretrip. Long-haul crews also reported taking a day longer to return to normal after a trip.

In summary, this study confirms that crewmembers on a variety of three-person long-haul trip patterns lost sleep at a rate expected to have cumulative effects on sleepiness and performance. Because the circadian clock did not synchronize to the duty/rest cycle, the circadian low point in alertness and performance sometimes occurred in flight. On these occasions, long-haul crews were working when sleep loss and circadian factors combined to produce the greatest vulnerability to performance errors. The present study suggests a number of ways in which these problems could be addressed.

With regard to the issue of cockpit alertness, the only countermeasure which addresses the underlying physiological sleepiness is sleep. The cockpit napping study already alluded to (29) clearly demonstrated improvements in performance (on a sustained attention, vigilance-reaction time test) and physiological alertness after crewmembers were allowed a preplanned 40-min nap opportunity in their cockpit seats. There is currently an FAA Notice of Proposed Rule Making to make cockpit napping legal in three-person long-haul operations. Careful consideration needs to be given to how cockpit napping might be safely implemented in two-person long-haul crews.

Until such time as supersonic travel enables crews to return to their home time zone each night, long-haul operations will involve crewmembers being in different time zones on consecutive layovers. It is not clear that circadian readaptation to a new time zone every 35 h is possible, practical, or desirable. One alternative is to design duty/rest schedules that are multiples of 24 h so that crewmembers can try to remain on home time throughout a trip pattern. If successful, this strategy would make times of peak sleepiness more predictable and facilitate layover sleep planning. It would eliminate the internal desynchronization between different physiological systems which is characteristic of jet-lag. By synchronizing the whole crew to the same time zone, it would reduce inter-individual variability, making it easier to design schedules meeting the physiological requirements of a larger proportion of crewmembers. While theoretically attractive, there are many practical considerations which may limit the feasibility of this approach. It would require dark, quiet sleeping accommodation and availability of meals at unusual local times in layover hotels. It would be facilitated if crewmembers minimized their exposure to local time cues during layovers (for example wearing dark glasses when exposed to sunlight and not adapting to the local social routine). Crewmember acceptance of such structuring of their layover activities would be a major issue. This approach would appear to be more feasible in military operations where larger groups of people are working on the same schedule.

The quantity and quality of sleep that crewmembers are able to obtain during layovers depends on a variety of environmental and physiological factors, including prior flight direction, the local day/night cycle and social routine, the circadian cycle, the duration of prior wakefulness (3), and age (19). This complexity, and individual variability, preclude simple universal solutions to the problem of sleep loss during long-haul operations. One useful approach to these issues is to provide crewmembers, schedulers, and regulators with education about sleep and circadian physiology together with practical information on countermeasures which they can tailor to their own needs and specific operational demands (28).

ACKNOWLEDGMENTS

This study was made possible by the enthusiasm and commitment of the flight crews, their union representatives, and the airline management. Mike Baetge, Paul Gallaher, and Don Hudson made critical contributions as cockpit observers and in many other capacities.

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Flight Crew Fatigue VI: A Synthesis

PHILIPPA H. GANDER, PH.D., MARK R. ROSEKIND, PH.D., AND KEVIN B. GREGORY, B.S.

GANDER PH, ROSEKIND MR, GREGORY KB. *Flight crew fatigue VI: a synthesis.* **Aviat Space Environ Med 69(9,Suppl.):B49–60.**

Sleep, circadian rhythms, subjective fatigue, mood, nutrition, and physical symptoms were monitored in flight crews before, during, and after scheduled commercial operations. Duty-related changes in these measures were examined in four different types of air transport: short-haul fixed-wing; short-haul helicopter; domestic overnight cargo; and long-haul. The extent of these changes, and the duty-related and physiological factors contributing to them, are compared among the different operations. During all operations, the level of sleep loss was such that the majority of crewmembers would be expected to have become increasingly sleepy across trip days, with some experiencing performance decrements. In addition, during overnight cargo and long-haul operations, crewmembers were sometimes flying aircraft during the circadian low point in alertness and performance. Specific recommendations for reducing flight crew fatigue are offered for each operating environment.

THE FOUR NASA FIELD studies described in the previous papers (15,19–21) provide an unprecedented amount of information on the duty-related and psychophysiological factors contributing to flight crew fatigue in different types of flight operations. Particular emphasis was placed on the two major physiological causes of fatigue symptoms in aviation, namely the disruption of sleep and circadian rhythms. Subjective fatigue and mood, changes in diet, and reports of physical symptoms were also recorded. All of the operations produced measurable changes in at least some of these variables. However, the extent of the changes, and the duty-related factors responsible for them, were different in each environment. This paper reviews the major findings, highlighting the similarities and differences among the operations, and examining specific ways in which fatigue in these operations could be reduced.

Duty Characteristics

In all of these studies, flight crewmembers were monitored before, during, and after regularly scheduled commercial trip patterns. **Table I** compares (by one-way analysis of variance) the characteristics of the trips studied. Information for Table I came from crewmembers' daily logbooks, and from the notes kept by the cockpit observers who accompanied them throughout each trip (17). The table includes only those trips for which sufficient sleep data were available to permit within-subjects comparisons of pretrip, trip, and posttrip values. Post hoc comparisons were made using Tukey tests with Bonferroni correction.

The daytime short-haul operations (fixed-wing and helicopter) permitted crewmembers to sleep at night and crossed a maximum of one time zone per 24 h. This caused minimal disruption to the circadian clock, which programs sleep at night and activity during the day, with a 24 h sleep/wake cycle. However both operations included multiple flight segments on each duty day and other demands which could potentially affect flight crew fatigue. The fixed-wing trips took place in the eastern and central U.S., with considerable flying in high traffic-density airspace. They included more flight segments per duty day, and the shortest layovers, of any of the operations studied ($p < 0.01$ for all comparisons), and longer duty days than all other operations except long-haul ($p < 0.01$ for all comparisons).

The helicopter trips serviced the North Sea oil fields from Aberdeen, Scotland. Operating conditions were often difficult with poor weather, variable quality landing sites with few alternates, limited automation of aircraft, and operating near the limits of range and performance capabilities of the aircraft. In addition, the cockpits were often physically stressful with such factors as poor ventilation, high levels of vibration, and uncomfortable temperatures due to solar heating and the requirement to wear cold-water immersion suits. Helicopter crews flew shorter duty days with fewer segments, and had longer layovers than their short-haul fixed-wing counterparts ($p < 0.01$ for all comparisons).

The domestic overnight cargo trips, which took place in the eastern and central U.S., involved multiple flights per night and crossed no more than one time zone per 24 h. They included fewer flight hours per 24 h than any of the other operations ($p < 0.01$ for every comparison), and fewer duty hours per 24 h than the other fixed-wing operations ($p < 0.01$ for all comparisons). The layovers were longer than those on the short-haul fixed-wing trips, but shorter than those on the long-haul trips ($p < 0.01$ for all comparisons). However, night duty required trying to override the normal diurnal orientation of the

From the Fatigue Countermeasures Program, NASA-Ames Research Center, Moffett Field, CA; San Jose State University Foundation (P. H. Gander); NASA-Ames Research Center (M. R. Rosekind); and Sterling Software, Inc. (K. B. Gregory).

Address reprint requests to: Philippa H. Gander, Ph.D., who is currently a professorial research fellow in the Department of Public Health, Otago University at Wellington School of Medicine, P.O. Box 7343, Wellington South, New Zealand.

TABLE I. OPERATION CHARACTERISTICS.

	Short-Haul Fixed-Wing	Short-Haul Helicopter	Overnight Cargo	Long-Haul	F
Mean # segments/24 h	5.1	3.0	2.8	1.2	416.0****
Mean flight hours/24 h	4.5	3.6	2.6	6.9	207.5****
Mean duty hours/24 h	10.7	7.3	7.1	10.2	93.4****
Mean layover hours/24 h	12.5	16.8	14.9	24.3	281.3****
Maximum time zones crossed/24 h	1	0	1	8	
Day or night flying?	day	day	night	both	
Trip duration	3–4 d	4–5 d	8 d	4–9 d	
Crew complement	2-person	2-person	3-person	3-person	
# crewmembers studied	44	22	34	25	

*** $p < 0.0001$.

circadian clock, and being out of step with the day/night cycle and the diurnal orientation of the rest of society (1,8,33,53).

The four long-haul patterns studied were return trips from the west coast of the U.S. to Singapore, New Zealand, and England, and from the east coast of the U.S. via Germany to India. Daytime and nighttime flights usually alternated. Duty days were longer than those in either helicopter or overnight cargo operations ($p < 0.01$ for both comparisons), and included 1–2 flights crossing multiple time zones. Long-haul crews had more flight time per duty day than any other group, and had the longest layovers ($p < 0.01$ for all comparisons). On these trips, neither the day/night cycle nor the duty/rest schedule provided a 24-h pattern to which the circadian clock could synchronize. In addition, the long duration of the flights might be expected to make these crews especially prone to the effects of time-on-task fatigue, including reduced vigilance and habituation (11).

Crewmember Characteristics

Individual attributes of the crewmembers monitored in each operations are compared (by one-way analyses of variance) in **Table II**. Information from Table II came from the Background Questionnaires completed by all participants. Post hoc comparisons were made using Tukey tests with Bonferroni correction.

The long-haul crewmembers were the oldest group ($p < 0.01$ for all comparisons). The short-haul fixed-wing crewmembers were also older than the overnight cargo and helicopter crewmembers ($p < 0.01$ for all comparisons). The same pattern was reflected in years of experience. Years of experience was taken as the largest value from among the following categories: years with present airline; years of military experience; years of airline experience; years of general aviation experience; other. For crewmembers who proceeded from military to commercial aviation, this statistic would represent an underestimate.

The long-haul crewmembers were heavier than the helicopter crewmembers ($p < 0.01$), and more morning-type than either the helicopter crews or the overnight cargo crews ($p < 0.01$ in both cases). This is consistent with the observation that people tend to become more morning-type as they get older. There is some evidence that older and more morning-type individuals may have more difficulty adapting to shift work and time-zone changes (23). On this basis, it could be argued that physiologically challenging long-haul operations should be by flown by younger crewmembers, rather than the current situation. However, it is not known to what extent experience can counteract the effects of age-related changes in sleep and the circadian clock to influence cockpit alertness and performance.

The helicopter crewmembers scored lower than the

TABLE II. CREWMEMBER CHARACTERISTICS.

	Short-Haul Fixed-Wing	Short-Haul Helicopter	Overnight Cargo	Long-Haul	F
Mean age (y)	43.0	34.3	37.6	52.7	56.77***
Mean experience (yr)	17.1	8.6	12.8	22.8	25.80***
Mean height (in)	70.6	70.7	70.2	71.0	0.59
Mean weight (lb)	174.8	164.8	178.4	181.6	3.63*
Personal Attributes Questionnaire					
Instrumentality	23.3	21.4	24.5	22.8	2.72*
Expressivity	22.3	19.6	22.9	22.1	3.43*
I + E	2.8	2.4	3.2	2.7	2.41
Work and Family Orientation					
Mastery	20.0	21.3	21.3	20.7	0.99
Competitiveness	12.6	12.3	13.2	13.6	0.82
Work	17.7	17.7	18.2	17.5	0.88
Eysenck Personality Inventory					
Neuroticism	6.6	8.2	5.1	6.6	2.19
Extraversion	10.9	9.5	11.0	9.4	1.42
Morningness/Eveningness	57.6	54.4	54.4	61.6	4.75**

* $0.05 > p > 0.01$; ** $0.01 > p > 0.001$; *** $p < 0.001$.

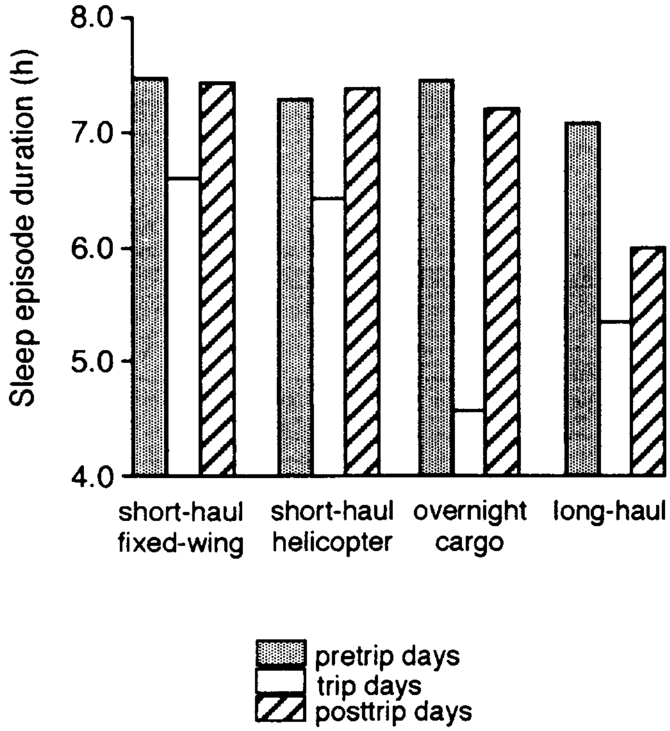

Fig. 1. Durations of individual sleep episodes on pretrip, trip, and posttrip days.

overnight cargo crewmembers on both the instrumentality and expressivity scales (27) of the Personal Attributes Questionnaire ($p < 0.01$ for both comparisons). It cannot be excluded that these differences were due to cultural factors, since the helicopter crews were British while the overnight cargo crews were U.S. citizens (the groups were comparable in age). Individuals scoring high on both scales have been reported to have better check airman ratings of flight crew performance (26) and to be more effective in group problem solving situations (41).

Duty-Related Changes in Sleep

Sleep quantity and quality were self-assessed in these studies. When they awoke from a sleep episode, crewmembers noted in their daily logbook the times of going to bed, falling asleep, waking up, and getting up. They also estimated how long they had slept (excluding time spent in bed awake) and how many times they had awakened during the sleep period. When they awoke from a nap, they noted the times of falling asleep and waking up. Long-haul flight crews have been shown to have a 95% probability of correctly estimating their objective sleep durations to within 0.5 h (10), but to be less reliable at estimating how long it takes to fall asleep, and how physiologically sleepy they are (24). It is not known how the reliability of other flight crews compares to that of the subjects in laboratory studies that have compared self-assessed and polygraphically recorded sleep parameters. Although subjective reports are less reliable than polygraphically confirmed sleep data, the measures used were internally consistent (16,20), and showed changes consistent with the different operational demands in each environment (15,19–21).

Duration of individual sleep episodes: In all operations, individual sleep episodes were consistently shorter on trip days than either pretrip or posttrip (**Fig. 1**). The changes in duration of sleep episodes across pretrip, trip, and posttrip days were compared among the operations by two-way ANOVA (**Table III**). The finding of shorter sleep episodes on trips was confirmed in the grouped data ($p(F) < 0.001$). Post hoc comparisons were made using Tukey tests with Bonferroni correction.

Sleep episode durations were not significantly different among the groups on pretrip or posttrip days. The significant interaction in Table III was due to the fact that, on trips, the overnight cargo and long-haul crewmembers had shorter sleep episodes than the short-haul fixed-wing crewmembers ($p < 0.01$ for overnight cargo, $p < 0.05$ for long-haul).

Quality of individual sleep episodes: On awakening, crewmembers rated their sleep quality (from 1 to 5) on the questions: Difficulty falling asleep?; How deep was your sleep?; Difficulty rising?; How rested do you feel?. These were converted so that higher scores indicated better sleep, and then added together to give an overall sleep quality rating. The changes in overall sleep quality across pretrip, trip, and posttrip days were compared among the operations by two-way ANOVA (Table III). Post hoc analyses indicated that trip sleep ratings were lower than posttrip ratings ($p < 0.01$), and tended to be lower than pretrip ratings ($p < 0.05$).

For each operation, pretip, trip, and posttrip sleep quality ratings (including the four individual ratings and the combined rating) were also compared by one-way analysis of variance, as reported in the preceding papers. These analyses indicate that, among the crewmembers who were consistently able to sleep at night during trips, the short-haul fixed-wing crews reported poorer sleep (20), whereas the helicopter crews did not (15). Possible reasons for this difference include:

- the fixed-wing crews were 9 yr older on average;
- they slept in layover hotels on trips, whereas the helicopter crews returned home each night;
- they markedly increased their alcohol consumption on trips by comparison with pretrip. Alcohol can facilitate falling asleep, but it also compromises sleep quality (4).

Overnight cargo crewmembers reported that their daytime sleep was lighter, less restful, and poorer overall than nighttime sleep (19). This contrasts with physiological recordings of daytime sleep among night workers in other industries (1) which indicate that daytime sleep is

TABLE III. DUTY-RELATED CHANGES IN SLEEP.

	F Pre/Trip/Post	F Flight Operation	F Interaction
Sleep episode duration (h)	67.10***	4.82**	7.51***
Total sleep per 24 h	49.81***	0.35	1.25
Overall sleep quality	5.84**	2.11	1.77

** $0.01 > p > 0.001$; *** $0.001 > p > 0.0001$.

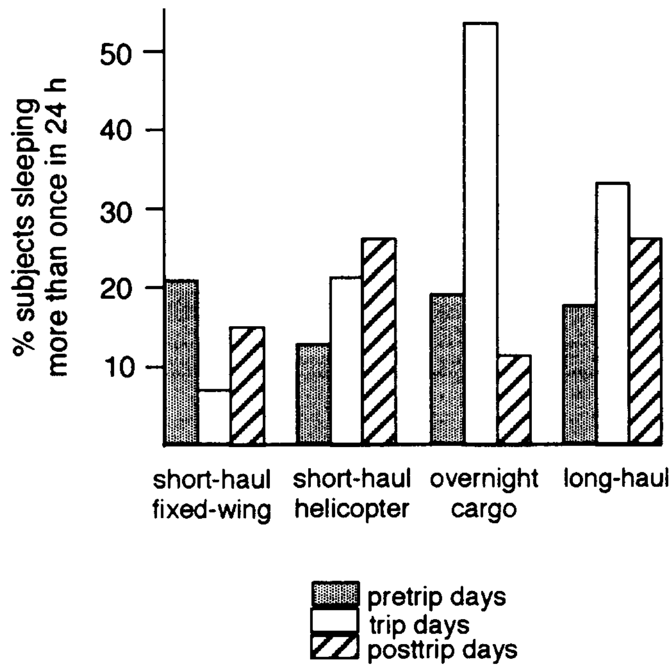

Fig. 2. Percentage of subjects sleeping more than once in 24 h (including naps) on pretrip, trip, and posttrip days.

usually shorter but deeper (deep slow-wave sleep being conserved at the expense of stage 2 NREM and REM sleep). The long-haul crewmembers did not report any significant changes in sleep quality on trips by comparison with pretrip (21).

Total sleep per 24 h: To compensate for markedly shorter sleep episodes on trip days, overnight cargo and long-haul crews tended to sleep more than once during each layover **(Fig. 2)**. It is somewhat misleading to consider the number of sleep episodes per 24 h during long-haul operations, because long periods of wakefulness associated with duty (average 20.6 h) alternated with layovers (averaging 24.8 h) during which crewmembers usually slept twice. In fact, long-haul crewmembers slept more than once in 68% of layovers, compared with 53% for overnight cargo crews. Long-haul layovers were significantly longer than overnight cargo layovers (Table I).

The changes in total sleep per 24 h across pretrip, trip, and posttrip days were compared among the operations by two-way ANOVA (Table III). Post hoc comparisons were made using Tukey tests with Bonferroni correction. Across all operations crewmembers averaged less total sleep on trip days (6.6 h) than on pretrip days (7.6 h) or posttrip days (7.7 h; $p < 0.01$ for both comparisons). This analysis did not find significant differences among the operations in the total amount of sleep per 24 h either pretrip, during trips, or posttrip. However, it does not take into account the greater prevalence of split sleep patterns during overnight cargo and long-haul trips. There was also considerable individual variability in sleep loss* in all operations. This is reflected in **Fig. 3**, which shows the percentages of subjects who averaged daily sleep gain or daily sleep loss across the different operations.

Cumulative sleep debt: Averaging a daily sleep loss across a trip pattern leads to the accumulation of a sleep debt. By the end of a 4-d short-haul trip, a crewmember averaging 2 h of sleep loss per 24 h would have lost a total of 8 h of sleep. By the end of the 8-d overnight cargo trips, even with the recuperation on the night off, 29% of crewmembers had accumulated a sleep deficit of more than 16 h, roughly equivalent to 2 complete nights of sleep. By the end of the 8-d "London" long-haul trip, 33% of crewmembers had accumulated a sleep deficit of more than 16 h.

Significance of duty-related changes in sleep: No objective measures of alertness or performance were collected during these studies, and no fatigue-related safety incidents were observed. Nevertheless, data from laboratory studies suggest that the observed levels of sleep loss might be expected to have reduced crewmembers' functional capacity in some cases.

Reducing sleep by 2 h on 1 night in the laboratory increases subsequent sleepiness and can impair performance on a variety of tasks. It also causes consistent changes in the structure of sleep (shorter sleep latencies and deeper, more consolidated sleep) that are considered to indicate insufficient sleep (7). The effects of reducing

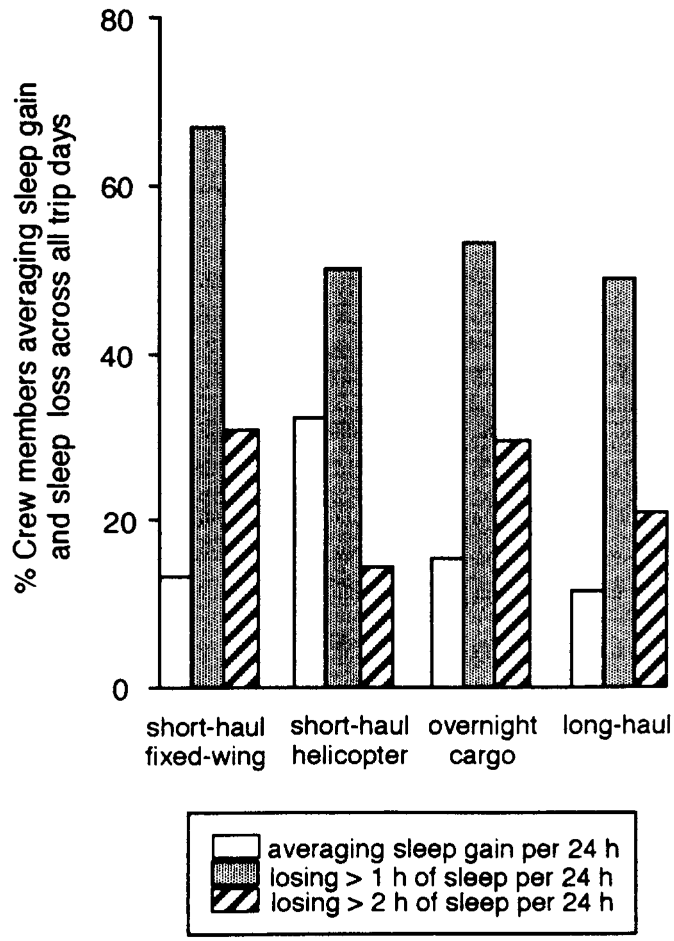

Fig. 3. Average sleep loss across the entire trip during different operations.

*To calculate individual sleep loss for each crewmember, his total sleep per 24 h on trips was subtracted from his average total sleep per 24 h at home pretrip.

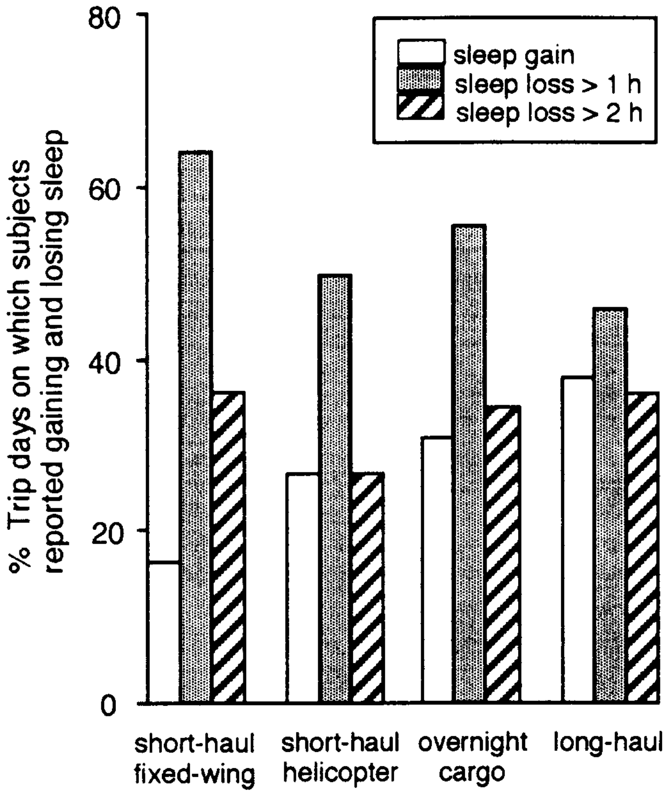

Fig. 4. Acute sleep loss (or gain) during different operations.

sleep by as little as 1 h per night accumulate over time to increase daytime sleepiness progressively (6).

Taking these values as benchmarks, the percentage of trip days on which crewmembers reported losing 1 or 2 h of sleep were calculated for each operation **(Fig. 4)**. The estimates of sleep loss during fixed-wing short-haul operations are exaggerated because a number of crewmembers took strategic naps on the final pretrip day (20). This inflated their total pretrip sleep duration, against which their subsequent sleep loss was calculated. Recall also that the long-haul crewmembers had a non-24 h duty/rest pattern. Fig. 4 suggests that, across all the operations, on any trip day about half the crewmembers were suffering from 1 h of acute sleep loss, and about one-third were suffering from 2 h of acute sleep loss. However, these figures may well underestimate the increased potential for error due to sleep loss on trips. They consider only the total sleep per 24 h and do not address the effects of split sleep during overnight cargo and long-haul layovers, or the effects of reduced sleep quality, which can also impair subsequent waketime function (47). Further, they do not address the cumulative effects when sleep is restricted across a series of consecutive days, as in these operations.

Individual attributes and duty-related sleep loss: A variety of analyses were carried out in an attempt to identify individual attributes that might explain the large variability in sleep loss observed among crewmembers during trips. Among overnight cargo crews (19), the average daily percentage sleep loss on trips was not correlated with any of the attributes reported by others to predict adaptation to shift work, namely: the amplitude of the pretrip baseline temperature rhythm (43,51); the neuroticism and extroversion scales of the Eysenck Personality Inventory (9,12,22); and morning/eveningness (2,13,28–30,33,35,50). A meta-analysis was carried out on a combined data pool from 91 U.S. commercial and military flight crewmembers aged 20–60 yr (23). Multiple regression analyses were used to assess the contributions of the following individual attributes to the variance in the average daily percentage sleep loss on trips: age; neuroticism; extroversion; morning/eveningness scores; the amplitude of the baseline temperature rhythm; and the local time of its daily minimum. The phase and amplitude of the baseline temperature rhythm were the only significant predictors of sleep loss while on duty, accounting together for about 8% of the variance. It should be noted, however, that the age distributions of crewmembers in each type of operation were different, so that different operational demands may have camouflaged the contribution of other (unidentified) age-dependent effects on sleep loss. In a combined data set of military and commercial long-haul crews ($n = 67$, age range 20–60 yr), there was a significant increase in the average daily percentage sleep loss on trips with age (one-way ANOVA with age in 10 yr bins, $F = 3.36$, $p < 0.05$).

Duty-related Changes in the Circadian Temperature Rhythm

In these studies, the time-course of the circadian clock was estimated from the rhythm of rectal temperature measured at 2-min intervals. To reduce the masking of the circadian variation in temperature by shorter-term fluctuations caused by changes in physical activity, a constant (0.28°C) was added to each crewmember's temperature data whenever he reported being asleep. The effects of this mathematical unmasking technique on estimation of circadian parameters have been described in detail elsewhere (18). Both masked and unmasked temperature data were subjected to multiple complex demodulation to estimate the times of the cycle-by-cycle minima (42).

In both the short-haul operations studied, layovers coincided with local night and no more than one time zone was crossed in 24 h. This permitted the circadian clock to remain synchronized to local time. However, during both operations, crewmembers averaged about 1 h of sleep loss per day because they were unable to go to sleep early enough to compensate for having to wake up 1.5 h earlier than usual to go on duty. Circadian factors oppose falling asleep earlier than usual. The evening wake maintenance zone is centered several hours before the usual bedtime (52). This is a part of the circadian cycle where it can be difficult to fall asleep, even with a moderate sleep debt. In addition, the innate period of the human circadian clock is usually around 25 h (52,55). Consequently, it is easier to fall asleep later than usual, rather than earlier. This effect is reinforced by the increase in sleep drive caused by staying awake longer (3,7). Thus, even in the short-haul operating environments, the circadian clock was restricting the amount of layover time that was available for sleep.

Overnight cargo operations required crews to fly for up to 5 consecutive nights, crossing no more than 1 time

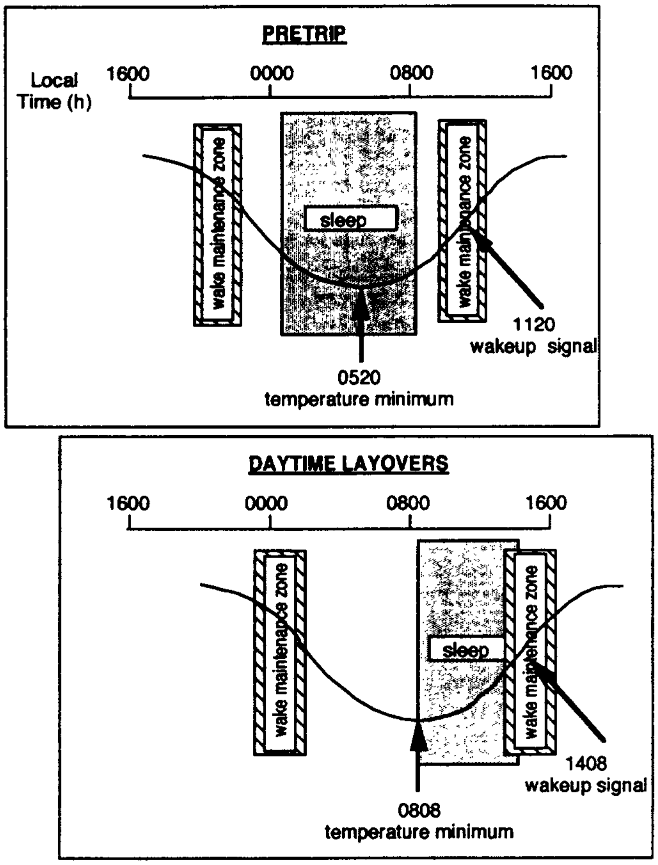

Fig. 5. Schematic showing the timing of sleep with respect to the circadian temperature rhythm, for overnight cargo crewmembers on pretrip and trip days. The average sleep times are indicated as shaded rectangles. The circadian temperature rhythm is approximated by the sinusoid, with the average time of the unmasked temperature minimum indicated. The timing of the wake maintenance zones and the wakeup signal have been extrapolated, based on reference 52.

zone per 24 h. In keeping with findings for night workers in other industries, the temperature rhythm showed minimal adaptation to night flying, delaying by an average of about 3 h (1,33,53). One consequence of this incomplete adaptation was that crewmembers were often on duty around the time of the temperature minimum (19). At this time, their physiological sleepiness and subjective fatigue would be expected to be greatest, and their performance to be poorest (1,9,31,32,34,47). Another consequence of incomplete circadian adaptation to night duty was that crewmembers were forced to sleep later in the circadian cycle after night duty than they did when they were able to sleep at night. This is illustrated in **Fig. 5.** It is noteworthy that the average time of waking up from morning sleep episodes was 1413 hours local time, and the average expected time of the circadian wakeup signal (6 h after the temperature minimum) was 1408 hours. Crewmembers did not record what caused them to wake up, but they did indicate that they did not feel well-rested after morning sleep episodes, which were markedly shorter than their normal nighttime sleep. These findings suggest that the circadian clock may well have been restricting the amount of layover time available for sleep.

In long-haul operations, the combination of non-24 h duty-rest cycles, alternating daytime and nighttime flying, and flights crossing up to 8 time zones, together created erratic environmental time cues that the circadian clock could not follow.[†] Some 80% of crewmembers continued to exhibit circadian variation in temperature, with an average cycle length of 25.7 h (SD 1.3 h). The remaining 20% of crewmembers had no detectable circadian rhythmicity in temperature. Because the average duty/rest cycle was about 35 h (Table I), the circadian temperature minimum, and hence the low point in alertness and performance, sometimes occurred in flight (21).

Sleep timing during long-haul layovers was linked to the circadian temperature cycle (21). This is illustrated in **Fig. 6.** During layovers, the average time of sleep onset was 2 min after the temperature minimum and the average time of wakeup was 6.4 h after the temperature minimum; or around the expected time of the circadian wakeup signal. This closely resembles the patterning of sleep observed with people living in time-free environments who spontaneously adopt a sleep/wake cycle dif-

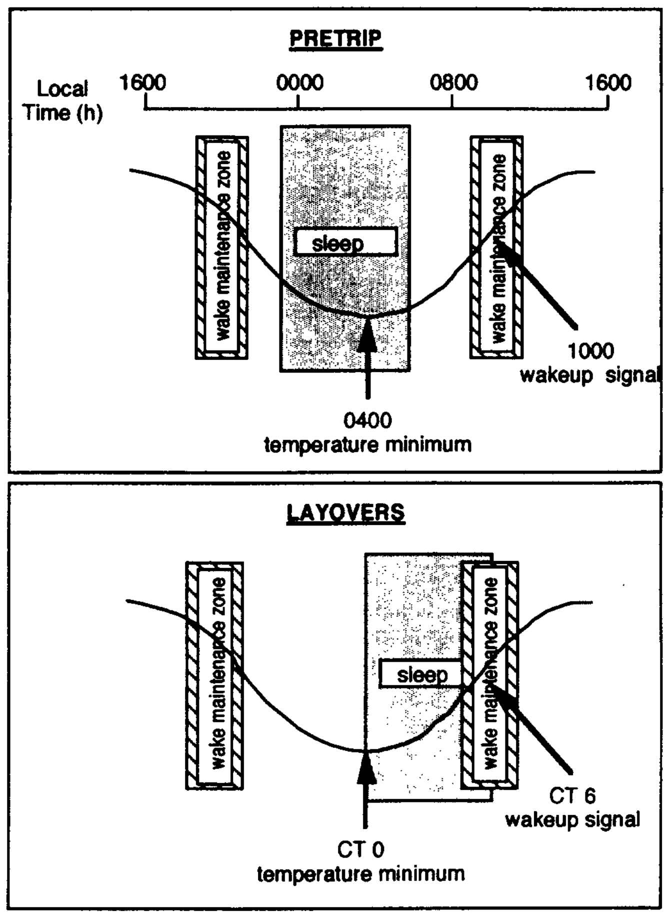

Fig. 6. Schematic showing the timing of sleep with respect to the circadian temperature rhythm, for long-haul crewmembers on pretrip and trip days (see Fig. 5 for explanation). During these operations, consecutive layovers were usually in different time zones, and the circadian clocks of most crewmembers drifted away from a 24 h cycle. Thus, neither local time nor GMT are suitable time reference scales for these data. They are therefore referenced to the circadian temperature cycle.

[†]Linear-nonlinear least squares iterative multiple regression was used to search for significant periodicities in the temperature data (48).

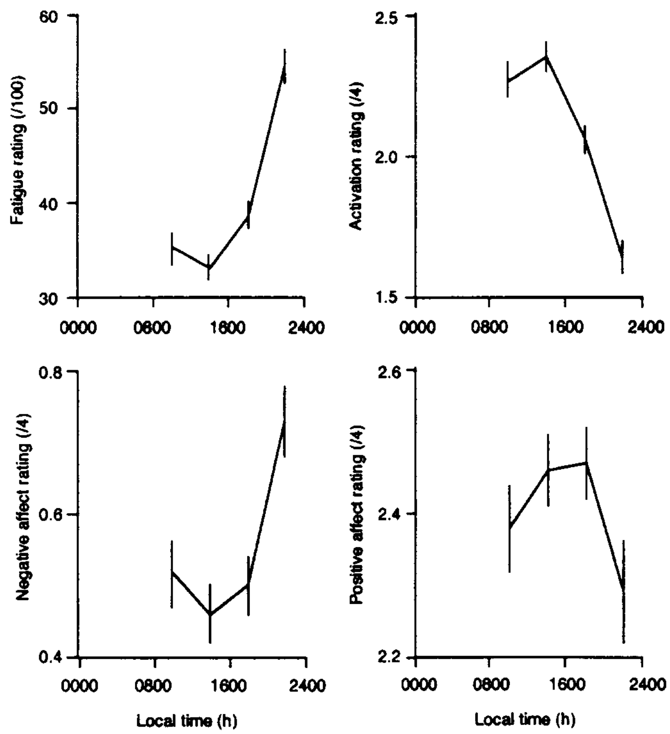

Fig. 7. Time-of-day variation in pretrip fatigue and mood ratings. These are combined data for 69 crewmembers from all four operations (one-way ANOVA with fatigue ratings in 4-h bins, $F = 52.0$, $p < 0.001$). Vertical bars indicate standard errors.

ferent from the period of the circadian temperature rhythm (52). On layovers, long-haul crewmembers were sleeping in a similar part of the circadian cycle to overnight cargo crewmembers. However, the long-haul crews selected to sleep at these times, within layovers averaging about 25 h, and they tended to sleep during local night. In contrast, the overnight cargo crews had layovers that averaged about 16 h and that were confined primarily to the daylight hours. Interestingly, the long-haul crews did not experience the reduction in sleep quality on trips that the overnight cargo crews reported.

Duty-Related Changes in Subjective Fatigue

Crewmembers indicated their subjective feelings of fatigue every 2 h while they were awake, by placing a mark on a 10-cm line from very alert to very drowsy. This measure of subjectve fatigue was not significantly correlated with how rapidly long-haul crewmembers fell asleep in Multiple Sleep Latency Tests conducted before and after the first segment of an international trip pattern (24). However, it was correlated with subjective sleepiness as measured by the Stanford Sleepiness Scale. Some studies have shown significant correlations between subjective sleepiness and physiological indicators of sleepiness, including increased alpha and theta activity in the EEG, and slow eye movements (1).

A marked time-of-day variation in subjective fatigue was evident on pretrip days (**Fig. 7**). Laboratory studies indicate that this type of fatigue measure includes two components: one that parallels the circadian temperature rhythm; and a trend to increasing fatigue with increasing duration of wakefulness (32).

In the daytime short-haul studies, crewmembers were rating their fatigue at the same times in the circadian cycle on pretrip, trip, and posttrip days. It was therefore possible to look for duty-related changes in fatigue. The fixed-wing crews did not report any significant changes (20). The helicopter crews reported feeling greater fatigue by the end of duty days than by the end of pretrip days (15). They also rated their overall fatigue as higher on posttrip days than on pretrip days, which could reflect an accumulation of subjective fatigue across the 4–5 d trips.

In both the overnight cargo and long-haul operations, wakefulness occurred during a different part of the circadian cycle on trip days by comparison with pretrip and posttrip. It was thus not possible to separate the effects of duty-related activities from the effects of sampling a different part of the circadian cycle. Both groups rated their fatigue as higher on trip days than on pretrip days (19,21).

Crewmembers were asked how often they felt that fatigue affected their performance during a typical trip (from 1 = never to 5 = frequently). Responses to this question do not appear to be age-dependent (19), and were not significantly different for the different operations (one-way analysis of variance, $F = 1.32$, $p = 0.27$). The average value of 2.9 indicated that crewmembers considered that fatigue sometimes affected their performance.

Duty-Related Changes in Mood

Each time that they rated their fatigue, crewmembers also rated their mood on 26-adjectives (36,37,40) which were separated into three categories: positive mood, negative mood, and activation (16). Combining pretrip data from 77 crewmembers from all four operations (Fig. 7), ratings on all the mood categories showed significant time-of-day variation (one-way ANOVAs: F (activation) $= 51.83$, $p < 0.001$; F (positive mood)$= 3.90$, $0.01 > p > 0.001$; F (negative mood) $= 17.42$, $p < 0.001$). However, looking at each operation separately, i.e., with smaller numbers of crewmembers, positive mood did not vary significantly across pretrip days (17,19–21). Likewise, negative mood did not vary significantly across pretrip days in the data from 12 overnight cargo crewmembers (19). A number of other studies have indicated that circadian variation is not always present in measures of mood states (32), probably because mood can be significantly affected by events occurring at the time that a rating is made.

There were no significant changes in mood ratings associated with the short-haul fixed-wing trips. The short-haul helicopter crews rated their activation as lower by the end of trip days than by the end of pretrip days, and going on duty earlier increased this effect (14). They also rated their negative mood as higher by the end of trip days than by the end of pretrip days, and staying on duty longer increased this effect.

For the overnight cargo and long-haul studies, the confound of duty-related effects and circadian effects on mood ratings could not be disentangled. Overall, overnight cargo crews reported lower activation and more negative mood on trip days than on pretrip days. This is

TABLE IV. DUTY-RELATED CHANGES IN NUTRITIONAL HABITS.

	Mean Short-Haul Fixed-Wing	Mean Short-Haul Helicopter	Mean Overnight Cargo	Mean Long-Haul	F
Appetite on trips	3.01	3.29	2.39	2.72	7.19***
Diet on trips	3.40	2.09	3.13	2.72	18.59***

*** $p < 0.001$.
Note: A value of 3.0 indicates no change on trips by comparison with home.

consistent with findings from other studies that negative changes in mood usually occur when the circadian system is disrupted (32). Long-haul crews reported lower activation, but no change in positive or negative mood, on trip days by comparison with pretrip days.

Overall, overnight cargo crews reported more impact of trips on subjective ratings (poorer sleep quality, less activation, more negative mood) than did long-haul crews who only reported reduced activation. An interesting speculation is that these differences might be linked to the different kinds of circadian disruption associated with the two environments. Overnight cargo crews remained in an environment with 24 h time cues, but were required to be active at an unusual time in it. In contrast, during trips, the long-haul crews had no consistent 24 h time cues from the environment, and their clocks desynchronized from it.

Duty-Related Changes in Dietary Habits

During all operations except overnight cargo, crewmembers increased their daily caffeine consumption on trips by comparison with pretrip (15,19–21). Caffeine is a central nervous system stimulant that can temporarily improve alertness, but can also disrupt sleep, causing longer sleep latencies and lighter, more broken sleep (4). Caffeine is also a diuretic, and may therefore exacerbate problems of dehydration in low humidity cockpits.

Crewmembers were asked (17) to rate how their appetite on trips compared with their appetite at home (from 1 = decreases to 5 = increases), and to rate the quality of their diet on trips compared with home (from 1 = worse to 5 = better). The responses for different operational groups were compared by one-way analysis of variance **(Table IV)**. Post hoc comparisons were made using Tukey tests with Bonferroni correction.

The overnight cargo crews reported significantly poorer appetite on trips than either of the short-haul groups ($p < 0.01$ for both comparisons). The long-haul crews also reported significantly poorer appetite on trips than the helicopter crews ($p < 0.01$). The helicopter crews reported a greater reduction in the quality of their diet on trips than any other group ($p < 0.01$ for all comparisons). The long-haul crews reported signifcantly poorer diet than the short-haul fixed-wing crews ($p < 0.01$).

In summary, the short-haul fixed-wing crews reported that their diet improved somewhat on trips with minimal change in appetite. The helicopter crews reported the greatest increase in appetite on trips and the greatest reduction in the quality of their diet. They were the only group that did not report an increase in snacking on trip days. Food was available in Aberdeen (where each duty day began and ended), and crewmembers could request meals on the rigs, but nothing was available in flight. These findings suggest that attention to the quality and quantity of food available during these operations might be beneficial. The overnight cargo crews reported the greatest reduction in appetite on trips, but with minimal change in the quality of their diet, although they reported eating more snacks. Their reduction in appetite could have been affected by the incomplete adaptation of the circadian clock to night work, since they were on duty at times in the circadian cycle when people would normally be asleep. The long-haul crews reported moderate reductions in appetite and in the quality of diet on trips. They were also the only group that reported eating fewer meals on trip days than on pretrip days. This may reflect problems obtaining suitable meals at unusual local times, as well as the fact that duty sometimes coincided with the part of the circadian cycle where people would normally be asleep.

Duty-Related Changes in Health

Shift workers in other industries generally have higher incidences of health complaints than day workers in comparable jobs, particularly sleep disruption and gastrointestinal problems (1,8,53). **Table V** compares the most common complaints of physical symptoms among crews flying the different operations from a checklist of 20 symptoms. The same four symptoms recurred as the most common in all operations.

In general, reports of symptoms increased on trip days, particularly for back pain and burning eyes (15,19–21). Reports of congested nose were common to all the fixed-wing operations, suggesting a possible effect of altitude and lower cockpit humidity. The helicopter cockpits were often physically stressful with high levels of vibration and thermal loading (14). The higher incidence of back pain among long-haul vs. short-haul fixed-wing crews may be related to the longer flight segments on long-haul (see Table I).

Crewmembers were asked (17) to rate their general health (from 1 = fair to 5 = excellent) and whether they experienced stomach or intestinal problems on trips that they did not experience at home (from 1 = never to 5 = frequently). The responses for different operational groups were compared by one-way analysis of variance **(Table VI)**.

No significant differences were found in either general health, which was rated as excellent, or in the additional incidence of gastrointestinal problems on trips, which was minimal. These findings are likely to have been influenced by the fact that all crewmembers had to undergo regular medical examinations to continue flying.

Crewmembers were also asked to indicate how long

TABLE V. PERCENTAGE OF CREWMEMBERS REPORTING THE MOST COMMON SYMPTOMS.

	Short-Haul Fixed-Wing	Short-Haul Helicopter	Overnight Cargo	Long-Haul
1st Symptom	Headache (27%)	Headache (73%)	Headache (59%)	Headache (56%)
2nd Symptom	Congested nose (20%)	Back pain (32%)	Congested nose (26%)	Congested nose (28%)
3rd Symptom	Back pain (11%)	Burning eyes (18%)	Burning eyes (18%)	Back pain (20%)

it took them to return to what they considered "normal" after a trip. The possible responses were: a) less than a day; b) 1 d; c) 2 d; d) 3 d; e) 4 d or more; f) does not apply. The responses for different operational groups were compared by one-way analysis of variance (Table VI). Post hoc comparisons were made using Tukey tests with Bonferroni correction. The short-haul fixed wing crews reported returning to normal faster than either the overnight cargo or the long-haul crews ($p < 0.0001$ for both comparisons). Long-haul crews took longer to return to normal after a trip than any other group ($p < 0.01$ for all comparisons). This order is consistent with the circadian disruption imposed by the different operations. The short-haul crews remained synchronized to domicile time during trips. The overnight cargo crews only partially adapted to their nocturnal duty times and rapidly reverted to normal on days off. The circadian clocks of the majority of the long-haul crews desynchronized from the environment during trips, and would therefore be expected to take several days to resynchronize to local time after their return home.

DISCUSSION

Comparing the findings from field studies of fatigue in different operations highlights the fact that operational demands vary, as do individual responses to those demands. This precludes a simple universal solution to the problems associated with fatigue in aviation. Each field study identifies specific ways in which fatigue could be reduced. These include possible changes to the Federal Aviation Regulations, alterations in the scheduling practices of individual airlines, and improving the personal coping strategies of individual crewmembers. This implies that responsibility for dealing with issues of fatigue rests with all members of the aviation community.

Countermeasures to reduce the potential impact of fatigue in flight operations can be divided into two categories: preventive strategies which are used prior to duty and during layovers; and operational countermeasures which are used in-flight to help crewmembers maintain their alertness and performance (45). The recommendations that follow are considered in these two categories.

Preventive strategies: Preventive strategies address the major physiological causes of fatigue in flight operations, namely sleep loss and circadian rhythm disruption. Sleep loss, whatever its origins, has detrimental effects on performance. Circadian rhythm disruption is an inevitable consequence of providing round-the-clock services and of transmeridian flight. It can compromise cockpit performance in two ways: through requiring crewmembers to be on duty during the part of the circadian cycle when their performance capacity and alertness are lowest; and through displacement of their sleep to parts of the circadian cycle when sleep quantity and quality, and therefore subsequent waking function, are compromised.

One area in which regulatory action may be warranted is in multi-segment short-haul operations. During the short-haul fixed-wing trips studied, the average daily flight time (4.5 h) was less than half the average daily duty time (10.6 h) and a third of all duty days were longer than 12 h (16,20). The nighttime layovers were the shortest of any of the operations studied (Table I), and the duration of the layover was the single most important scheduling factor contributing to sleep loss. Currently, the FARs define minimum rest requirements based on the number of flight hours. These data suggest that it may be necessary in this environment to regulate duty hours and to relate rest periods to duty hours rather than, or in addition to, flight hours. Since this study was conducted in the mid-1980s, the short-haul operating environment has become considerably more competitive, and the same issues are relevant in the burgeoning regional and commuter airline sectors.

The current Federal Aviation Regulations limit flight hours and determine rest requirements independent of the time-of-day of flying. Based on the data, particularly from the overnight cargo and long-haul operating environments, we would advocate that this position be carefully reconsidered. A number of other countries have already incorporated circadian factors in their flight and duty time regulations (54) and these could be examined as models. It is important to recognize that the FARs serve only as guidelines within which companies decide their scheduling policies through negotiation with their employees. Thus regulatory changes may be necessary, but will certainly be insufficient to deal with all aspects of these problems.

A number of scheduling recommendations arise from

TABLE VI. DUTY-RELATED CHANGES IN HEALTH.

	Mean Short-Haul Fixed-Wing	Mean Short-Haul Helicopter	Mean Overnight Cargo	Mean Long-Haul	F
General health	4.31	4.22	4.40	4.31	0.33
Stomach/intestinal problems	1.78	1.72	1.64	2.13	1.54
Return to normal	1.76	2.22	2.34	3.25	18.49***

*** $p < 0.001$.

the fatigue field studies. One general principle arising from circadian physiology is that the timing of a layover can be as important as its duration in providing adequate time for crewmembers to sleep. As an example, in both the fixed-wing and helicopter short-haul operations, early duty report times were a significant contributor to sleep loss (14–16,20). Crewmembers were unable to fall asleep sufficiently early to compensate, in part because of the evening wake maintenance zone (52). The helicopter crewmembers averaged only 6.4 h of sleep in layovers averaging 16.8 h. In these operations, the time of going on duty the next morning accounted for 41% of the variability in sleep duration, while the layover duration did not have a statistically significant effect (14,15).

In the short-haul fixed-wing schedules there was another common scheduling practice that would be expected to contribute to sleep loss. On average, duty days began progressively earlier across the 3–4 d trips. This effectively restricts the time available for sleep progressively across the trip. In addition to the problem of the evening wake maintenance zone, the biological day programmed by the circadian clock tends to be longer than 24 h, making it easier to adapt to duty days which begin progressively later. Thus, wherever possible, successive duty days should begin at the same time or progressively later, rather than earlier.

During the overnight cargo trips studied, both the timing and duration of layovers had important effects on sleep loss. The earlier a crewmember finished duty in the morning, the longer he was able to sleep before the circadian wakeup signal (around 1400 hours local time). The time of getting off duty accounted for 44% of the variability in the duration of these morning sleep episodes (19), which averaged 2–3 h shorter than pretrip nighttime sleep episodes. The duration of the layover determined whether crewmembers had sufficient time to sleep again before the next night duty. Layovers in which they slept twice averaged 19.3 h, while layovers in which they slept once averaged only 14.8 h.

Scheduling en-route layovers during long-haul operations to ensure that crewmembers obtain adequate sleep is a very complex challenge. Data from the fatigue field study suggest that the factors to be considered include: previous transmeridian flights in the sequence; the direction of the preceding flight; whether it was a daytime or a nighttime flight; the timing of the layover with respect to local night; and the timing of the layover with respect to the circadian cycle of each crewmember. From a physiological point of view, the ideal layover would include a sleep opportunity where the circadian temperature minimum occurred between about 0200 and 0600 hours local time. (The average time of the pretrip temperature minimum in the crewmembers studied was about 0400 hours local time; see Fig. 6). In practice, it is very difficult to predict the time of the temperature minimum through a sequence of non-24 h duty-rest cycles with multiple transmeridian flights. One potential solution would be to make duty-rest schedules multiples of 24 h, in order to keep crews synchronized physiologically to home time. If this approach worked, it would help alleviate the sleep disruption and other problems associated with jet-lag. It would also reduce the range of individual variability in circadian phase, making it easier to design schedules adapted to the needs of a larger proportion of crewmembers, and to predict times of peak sleepiness during duty. The latter would permit more systematic use of operational countermeasures (see below). Although it is theoretically attractive, the feasibility and acceptability of this approach have never been rigorously tested.

Well-designed regulations and scheduling practices are necessary but not sufficient to minimize avoidable fatigue in aviation operations. Individual crewmembers also have a responsibility to try to report for duty well-rested and to make optimal use of their en-route layover time to obtain adequate sleep. In its investigation of a 1993 accident (39) involving the stall, loss of control, forced landing, and overrun of an Embraer EMB-120 RT at Pine Bluff, AR, the National Transportation Safety Board concluded:

> "The crew rest periods scheduled for the trip sequence were within company guidelines and FARs. However, the crew did not take advantage of the rest periods, and the combined effects of cumulatively limited sleep, a demanding day of flying, and a time of day associated with fatigue, were factors in the crew's inadequate judgement and performance".

As a result of its investigation into this accident, and into the 1993 loss of a Douglas DC-8-61 at Guantanamo Bay, Cuba (38), the Board has recommended that education about fatigue and fatigue countermeasures be required for both Part 135 and Part 121 air carriers. Recognizing the importance of education as a key preventive strategy, not only for flight crews but for everyone involved in aviation, the NASA Fatigue Countermeasures Program has developed an education and training module on alertness management in flight operations (17,44).

As mentioned previously, preventive strategies primarily address the two main physiological causes of fatigue, namely sleep loss and circadian disruption. While there is still much to be learned, there is currently a considerable amount of useful information available about practices which promote good sleep, factors which disrupt sleep, sleeping medications, and sleep disorders. By comparison, current understanding about how and when to manipulate the circadian clock is less mature. There is considerable interest in chronobiotics–drugs, hormones (e.g., melatonin), and other treatments (e.g., bright light) that are potentially capable of accelerating the adaptation of the circadian clock to a new duty/rest schedule or time zone. However, there are a number of practical considerations that, for the moment, limit the potential usefulness of chronobiotics for flight crews. The time in the cycle at which a chronobiotic is administered is critical, and opposite effects can be achieved by displacing the dose by several hours. Unfortunately, there is no simple single measurement which can give an indication of exactly where a crewmember is in the circadian cycle at any given time. Chronobiotics used in everyday life must act against a background of all the other environmental time cues to which an individual is exposed. While there are ways of minimizing these extraneous cues (e.g., wearing dark glasses to reduce the effects of sunlight, or minimizing contact with the local social environment), crewmember acceptance of, and compliance with, fatigue countermeasures which require such regimentation of layover activities is a real issue. There are also concerns about the effects of long-term use of potential chronobiotics across the working life of a flight crewmember. More fundamentally, it is not clear that circadian adaptation to local time is necessarily desirable in all situations. Adaptation to a duty/rest schedule then requires readaptation to nighttime sleep and local time on days off. For example, a survey study of 101 Lufthansa flight crews on polar schedules (Frankfurt via Anchorage to Tokyo or Seoul and return) lasting 7–11 d found that the sleep debt accumulated during the trip was less when crewmembers remained longer at the destination layover (49). Presumably sleep improved as the circadian clock adapted to local time. However, readaptation on return to Frankfurt was also slower when crewmembers stayed longer at the destination layover. Finally, none of the chronobiotics currently being considered has been shown to be effective in field tests in any aviation environment.

Operational countermeasures: Operational countermeasures are techniques that crewmembers can use in flight to help maintain their alertness and performance (45). Cockpit napping is currently receiving considerable attention. Observations from the long-haul fatigue field study indicated that about 11% of crewmembers were taking the opportunity to nap when conditions permitted (45). A recent NASA/FAA joint study has demonstrated that providing a preplanned 40-min nap opportunity in flight can improve physiological alertness and performance (on a sustained attention, vigilance-reaction time test) through to descent and landing (46). The limited duration of the nap is important to minimize the possibility of crewmembers entering into deep slow-wave sleep, and thus being prone to sleep inertia should they have to be awakened in an emergency. The FAA currently has a Notice of Proposed Rule Making that would legalize controlled napping in non-augmented three-person long-haul crews. The use of controlled cockpit napping in two-person long-haul crews requires careful consideration.

Except on flights exceeding 12 h, for which additional crewmembers are required, the current FARs (121.543) stipulate that "...each required flight crewmember on flight deck duty must remain at the assigned duty station with seat belt fastened while the aircraft is taking off or landing, and while it is en route." Since physical activity is a good short-term countermeasure for sleepiness,.consideration should be given to relaxing this restriction, with appropriate procedural safeguards.

Companies could contribute to operational countermeasures by developing cockpit procedures that pay specific attention to enhancing crew interaction and maximizing the active involvement of crewmembers in the operation. Declines in physiological alertness during long-haul flights have been shown to occur after periods without communication in the cockpit, and to occur simultaneously for the captain and the copilot on many occasions (5). Aircraft manufacturers could assist with this problem through the creative use of automation to enhance cockpit alertness, rather than to diminish it (5,25). Companies also have the opportunity to be proactive in providing education and training for all personnel about alertness management.

The success of any operational fatigue countermeasure ultimately depends on individual flight crewmembers. Appropriate education can provide them with a basis for assessing the feasibility and effectiveness of different countermeasures strategies in relation to their specific operational and personal needs. Admitting to fatigue has often been associated with negative connotations, such as laziness or lack of motivation. Recognizing that it has physiological causes should help to dispel these myths. To be effectively managed, fatigue in the cockpit needs to be dealt with explicitly by the individual and the crew.

ACKNOWLEDGMENTS

The Fatigue Countermeasures Program has benefited from the skills and dedication of many people. The foresight of John Lauber, Charles Billings, Curt Graeber, and Clay Foushee, who established the Program, has given aviation a considerable lead over many other industries in dealing with fatigue issues. Jerry Noga, Don Hudson, and Linda Connell made important contributions. Kevin Gregory, Donna Miller, Roy Smith, Herb Schreiber III, and Bill Carson have provided exceptional support in the area of data management and analysis. Dave Dinges has been an invaluable mentor and colleague. Liz Co has played a key role in the education and training activities of the Program. Long-term funding support from NASA and the FAA have brought this extensive body of work to fruition. The commitment and enthusiasm of the participating airlines and flight crewmembers has continued to be the driving force for the Program. The authors thank Pamela Day and Evynn Blaher for their key contributions to the editing, coordination, and production of this special supplement.

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